REPORT FOR THE MPV DEMONSTRATION AT NEW BOSTON AIR FORCE BASE, NEW HAMPSHIRE

ESTCP MR-201228: UXO Characterization in Challenging Survey Environments Using the MPV

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DEMONSTRATION REPORT
Project: MR-201228

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ACRONYMS AND ABBREVIATIONS

AFS	Air Force Station
AHRS	Attitude and Heading Reference System
BTG	Black Tusk Geophysics, Inc.
BUD	Berkeley UXO Discriminator
CFR	Code of Federal Regulations
cm	Centimetre
CO	Colorado
CRREL	Cold Regions Research and Engineering Laboratory (ERDC)
DAQ	Data Acquisition System
DGM	Digital Geophysical Mapping
EM	Electromagnetic
EMI	Electromagnetic Induction
ERDC	Engineering Research and Development Center
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
GW	George West
HASP	Health and Safety Plan
IDA	Institute for Defense Analyses
IVS	Instrument Verification Strip
m	Metre
mm	Millimetre
ms	Millisecond
MPV	Man Portable Vector
ms	Millisecond
MR	Munitions Response
NB	New Boston
NH	New Hampshire
PI	Principal Investigator
POC	Points of Contact
RTK	Real-time Kinematic
s	Second
SERDP	Strategic Environmental Research and Development Program

SNR	Signal to Noise Ratio
SVM	Support Vector Machine
TEMTADS	Time Domain Electromagnetic Towed Array Detection System
UXO	Unexploded Ordnance
YPG	Yuma Proving Ground

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EXECUTIVE SUMMARY

The Man-Portable Vector (MPV) technology was tested at a live site at the New Boston Air Force Station in New Hampshire in August of 2013 to demonstrate detection and classification of munitions at a densely wooded site as part of the ESTCP Live-Site Program for Munitions Response. This document reports on the data collection and analysis for that study.

The MPV is an electromagnetic induction (EMI) sensor designed for munitions detection and classification. This second-generation sensor has a handheld form factor that provides enhanced portability and ruggedness relative to vehicular-based systems. The sensor head is a 0.5-meter diameter disk that includes a vertical transmitter and an array of five three-component receivers. The MPV supports multiple deployment modes: dynamic data collection along survey lines to map UXO contamination; static, cued interrogation of selected anomalies to acquire the highest data quality for classification. The latter requires accurate positioning that can be supported by GPS in open sky conditions or with an EMI beacon in less favourable conditions, using a custom local positioning system with similar accuracy as GPS over short distances (4 meters). Prior to this study, the technology had been successfully demonstrated at four sites as part of the ESTCP program: Yuma Proving Ground (2010), Camp Beale (2011), Spencer Range (2012) and George West (2012). The technology had been tested for detection and classification with static and dynamic data under multiple environmental conditions: open field, low density forests and steep sided hills.

The New Boston site brought new challenges with an anomaly density of 3000-5000 anomalies per acre, at least ten times as high as that of previous studies, and a densely wooded forest that covered half of the one-acre study area. The tree density and ground conditions with deadfall and boulders were such that only a handheld instrument could be used. These conditions also caused navigation challenges as the tree canopy blocked GPS signal reception. Detection mapping and re-acquisition of anomalies relied on physical lines and custom positioning methods. The study area was expected to host 20 mm projectiles as well as landmines, practice rockets and bombs, HE bombs and incendiary bombs. The site hosted demonstrations with the MPV and the 2x2 TEMTADS, both with crews from CH2MHill. Each study was independently conducted under the technical guidance of the ESTCP and USACE.

The study started with a detection mapping survey for 0.5 acre of open filed pasture and 0.5 acre in the adjacent forest. The data were collected along 1-m wide lanes while regularly sweeping the sensor head side to side. Positioning in the forest was predicted from the variation of the sensor heading, for the position across track, and time along track. The data were immediately analyzed and a list of detected anomalies was submitted. In coordination with the USACE a subset of 450 anomalies was selected for cued interrogation. Reacquisition in the forest was based on indications of the line number, distance along line and lateral offset. These indications served as a starting point for a dynamic search with the "dancing arrows" to locate the source location, generally located within 0.3 m, before proceeding with cued interrogation.

Classification was performed on the cued data. The objectives of correctly classifying 95% of the TOI and rejecting 40% of the clutter were achieved, as well as most of the other objectives. The production rate goal was not met due to problems with the data acquisition software, which suffered from some instability related to the attitude and heading sensors, critical for positioning.

These issues caused a two-day delay in field operations as it required software modifications and troubleshooting. The field crews also found the ergonomics of the sensor to be difficult and tiring. Ergonomics are significantly improved in the third generation MPV.

1.0   INTRODUCTION

The demonstration at New Boston (NB) Air Force Station (AFS) is one in the series of Environmental Security Technology Certification Program (ESTCP) demonstrations of classification technologies for Munitions Response (MR). This demonstration was designed to investigate the evolving classification methodology at a site that included a densely wooded area which posed an accessibility challenge due to boulders, roots and tight vegetation, and a positioning challenge because GPS signals cannot penetrate thick canopy. The site was also suspected to contain a large variety of munitions down to 20 mm projectiles.

This project demonstrated the detection and classification potential of the Man Portable Vector (MPV) sensor at NBAFS. The MPV is a handheld sensor with a relatively compact form factor (Figure 1). The MPV uses electromagnetic induction (EMI) technology and was specifically designed to extend advanced classification capabilities to sites with challenging surveying conditions and reach most human trafficable land locations at moderate cost. A dedicated positioning system can be used to locate the sensor in the vicinity of a location of interest.

A typical site characterization study starts with a full-coverage mapping survey to detect and locate potential targets of interest. Locations with significant signal anomaly are subsequently investigated in cued interrogation mode, where data of the highest quality are collected for characterization and classification.

This project is also the opportunity to test the technology with a commercial operator. CH2MHill supplied two geophysicists to assist with the data collection. The crews were trained to operate the technology, in particular to handle the sensor to collect acceptable data, to assess the data quality and to predict the target location for optimal cued interrogation.
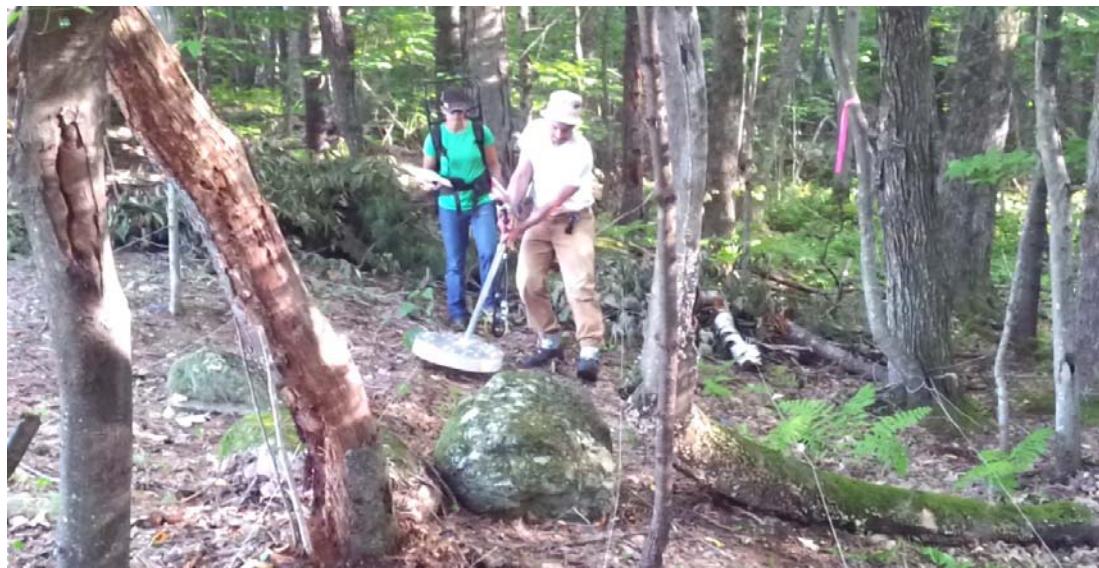
Figure 1.   Detection Survey with the MPV among Dense Trees and Boulders

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2.0   TECHNOLOGY

2.1   MPV TECHNOLOGY DESCRIPTION

2.1.1   Electromagnetic sensor

The MPV is a handheld sensor with wide-band, time-domain, EMI technology. The sensor presented in this study is the second-generation prototype MPV, which was deployed with the same hardware configuration at Spencer Range and Camp George West (ESTCP MR-201158). The sensor head is composed of a single transmitter coil and an array of five receiver units that measure all three components of the EM field (Figure 2). This second-generation MPV is specifically designed to (1) be man portable and therefore easy to deploy, manoeuvre and adapt to a survey environment, and (2) acquire data that is suitable for discriminating unexploded ordnance (UXO) from non-UXO targets. The MPV head is a 50-centimenter (cm) diameter transparent disk. The transmitter coil is wound around the disk and intermittently illuminates the subsurface. Five receiver units (cubes) measure the three orthogonal components of the transient secondary EM field decay with three air-induction coils wound on the faces each 8-cm side length cube.

The MPV is a programmable instrument. The duration of the excitation and time decay recording can be adjusted to accommodate the specific needs of target detection and classification. The detection survey consists of a full-coverage sweep where dynamic data are collected for digital geophysical mapping (DGM). Fast EMI transmit-receive cycles are applied so that the sensor can continuously move. The quality of detection data may not always be sufficient for target classification. In such cases a target is reacquired in cued interrogation, where data quality is to be maximized. The sensor is static to stack the recorded signal and reduce noise. Longer EMI cycles are applied to capture variations in time decay rates. This late-time information has been shown to improve distinction between intact ordnance and thinner walled shrapnel and cultural debris (Billings et al., 2007).

The MPV is a handheld sensor. The sensor head weighs 6 kg and the backpack-mounted data acquisition (DAQ) and batteries weight approximately 13.5 kg. Existing sensors with multiple time channel measurement capabilities (e.g., Berkeley UXO Discriminator [BUD], Geonics EM63, Time Domain EM Towed Array Detection System [TEMTADS]) are required to be mounted on a cart platform due to the size and weight of the multiple coils of wire required for the transmitters and receivers.

The MPV user interface has real-time data monitoring capabilities. The recorded data can be displayed to verify data quality and detect potential disturbances such as presence of magnetic soil or a damaged receiver. The past and present sensor location is displayed on a map along with preset survey points to verify spatial coverage and global location. A target detection and location tool indicates the origin of measured EMI fields with arrows (the so-called "dancing arrows" in top left corner of control display, Figure 2 inset). These features assist the field operator in efficient data collection, so that detection and classification data can be collected as part of the same survey, thus limiting the need to revisit an anomaly for further characterization.
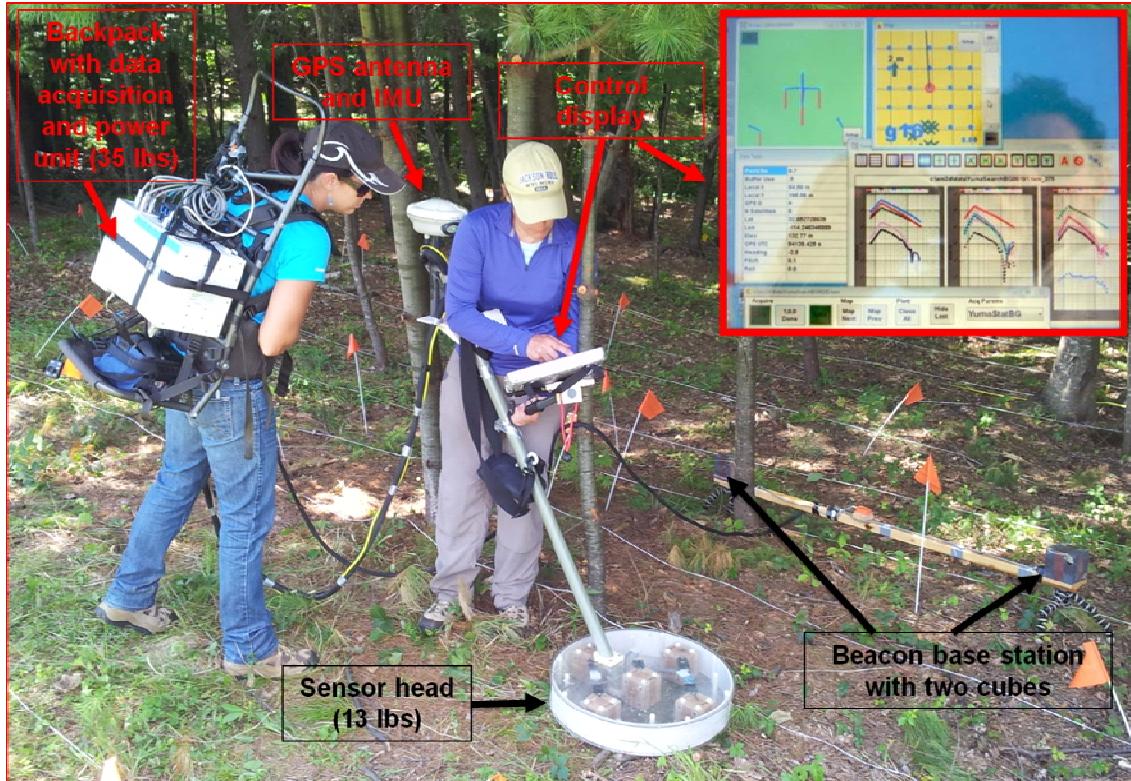
Figure 2. **The MPV Technology Components are shown in Cued Interrogation Mode at NBAFS.**

The sensor head is made of a transparent disk that contains a circular transmitter wound around the side and five 3D receiver cubes. A touch-screen display controls survey parameters and acquisition events (right inset). The data acquisition system and batteries are mounted on a backpack frame carried by the second operator.

Positioning can be achieved with GPS (only in open field) or a beacon boom (cued interrogation).

2.1.2 Geolocation

The sensor requires positioning for detection and classification, though with different spatial accuracy requirement. Therefore a field survey with the MPV can utilize two complementary positioning systems. Detection mapping has coarse decimeter-level accuracy requirements and can be performed with a GPS in open field, or using a method for tracking the distance along a line in the absence of GPS. The sensor head location is derived from the GPS rover location using the XSens MTi 3-axis Attitude and Heading Reference System (AHRS) sensor unit that is mounted at the base of the GPS mast.

Classification is based on geophysical inversion of multiple soundings and generally requires centimeter-level sensor positioning when surveying a target (Bell, 2005). The MPV was designed to extend UXO classification to difficult survey environments. The MPV technology incorporates a local positioning system that remains accurate in steep terrain and under thick tree canopy, where GPS positional accuracy is degraded. The beacon positioning system (San Filippo et al., 2007; Lhomme et al., 2011) consists of locating the origin of the MPV transmitter with a pair of EMI receivers rigidly attached to a portable beam that serves as a base station (Figure 2).

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The horizontal and vertical location of the center of the MPV head and its roll and pitch can be predicted from the beacon measurements. The heading is provided by the AHRS sensor that also records roll and pitch, which in return can be compared with the predicted roll and pitch for quality control. Field trials showed 1-2 cm and 1-2 degrees accuracy for position and roll-pitch – similar to GPS and attitude sensor – out to distances of 3-4 meters (m).

2.2 MPV TECHNOLOGY DEVELOPMENT

The project was initiated in 2005 under the Strategic Environmental Research and Development Program (SERDP) MM-1443. The project was led by Drs. Kevin O'Neill and Benjamin Barrowes with the Cold Regions Research and Engineering Laboratory of the Engineering Research and Development Center (CRREL, ERDC) in Dartmouth, New Hampshire (NH). The first MPV prototype was built in 2005-2006 with David George of G&G Sciences, Grand Junction, Colorado (CO). It was tested in 2007 at ERDC in a laboratory setting. Data analysis showed that stable target parameters could be retrieved and used for UXO classification.

The SERDP project was first extended in 2008 to continue testing. Field trials were done on a test plot to assess static and dynamic acquisition mode over buried targets. Stable target parameters were recovered. Effect of magnetic soil on EMI sensors was investigated. Adverse soil effects could be defeated owing to the MPV's array structure. The positioning system – ArcSecond laser ranger – proved to be impractical for field application due to line-of-sight requirement for all three rovers and tedious calibration. The SERDP project was extended with BTG personnel involvement in 2009 to test an alternative positioning system based on the beacon concept and prepare modification of the original MPV prototype for extensive field deployments. The sensor head was redesigned with lighter materials and a smaller head diameter to reduce weight and improve maneuverability while maintaining its expected performance (Lhomme, 2011b). Receivers were brought inside transmitter coil to reduce fragility; transparent material was employed to see the ground through the unit. Actual fabrication of the new head and replacement of the DAQ began under that SERDP funding extension.

Funding was obtained in 2010 in ESCTP MR-201005 to continue developing the MPV and performing field demonstrations. The MPV fabrication was completed. The MPV was successfully demonstrated at YPG UXO test site in October 2010 and at former Camp Beale in June 2011. In ESTCP MR-201158 the MPV was successfully demonstrated at Spencer Range, TN in June 2102 and at former Camp George West, CO in October 2012.

2.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY

The MPV is the only available handheld sensor that can acquire multi-static, multi-component data on a wide and programmable time range. The MPV offers several key benefits:

- Hand-held form factor: The MPV can be deployed at sites where terrain and vegetation preclude use of heavier, cart-based systems. Portability can improve productivity in rough terrain. The system is easy packable and transportable;
- Five receivers simultaneously record three orthogonal components of EM field with near-perfect relative positioning among receivers. Multi-component, multi-axis design reduces number of soundings for target characterization and relaxes positional accuracy

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(Grzegorczyk et al., 2009). Test with low-noise test-stand MPV (first generation) data showed that UXO could be identified with as few as 5 soundings (Barrowes et al., 2007). This was confirmed at YPG and Camp Beale.

- Magnetic soil can be detected and defeated: The geometric arrangement of receivers and the wide-band time range offer potential for identifying and neutralizing the effect of magnetic soil through techniques developed in SERDP MM-1414 and MM-1573.

Fully programmable through field display: Graphical field-user interface controls acquisition parameters such as transmitter waveform characteristics, duration of excitation, number of measurement cycles, stacking and recorded time channels.

- Highly stable EMI components: Responses are directly predictable using standard EMI theory. Field tests verified that MPV components had imperceptible measurement drift and were largely insensitive to survey conditions.

- Small target characterization: Small items have localized, rapidly-varying spatial response. Voltage in an air induction receiver coil is an average of a target scattered field through the face of the loop. Therefore, large receivers tend to "smear out" secondary fields. The MPV's 8 cm square coils are typically smaller than most multi-channel sensors (e.g., Geonics EM63 has 50 cm loops and TEMTADS has 25 cm) and thus better suited to detecting and sampling signals from small targets.

Portability has limitations: with a single transmitter, multiple soundings must be collected to characterize a target. Therefore the MPV requires (1) an accurate positioning system for cued interrogation and (2) manual intervention to move the sensor, which reduces productivity relative to a multi-transmitter platform for which a single sounding is often sufficient.

3.0 PERFORMANCE OBJECTIVES

This project includes data collection in dynamic detection and cued interrogation, data analysis and user feedback for evaluation of the MPV technology. The specific objectives for each stage are detailed in Table 1. These objectives depend on the intrinsic data quality of the sensor, the deployment method and the ensuing data analysis and interpretation.

Table 1.   Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria	Result
Data Collection Objectives				
Spatial coverage in detection survey	Extended footprint coverage	• Mapped survey data	98% coverage with 70 cm footprint in open field	Met: 99% coverage
Station spacing	Distance between soundings	• Sensor location	80% of data points with 0.1 m spacing and 95% with 0.15 m	Met: 85% within 0.1m spacing and 98% within 0.15 m
Repeatability of Instrument Verification Strip (IVS) survey	Amplitude of EM anomaly Amplitude of polarizabilities	• Twice-daily IVS survey data	Factor 2 on detection amplitude and 1.5 on target size	Met: Factor 1.5 on amplitude and size
Cued interrogation of anomalies	Instrument position	• Cued data	100% of anomalies where center of cued pattern is located within 0.5 m of anomaly pick	Met: 100% within 0.5 cm
Detection of all targets of interest (TOI)	Percent detected of seeded anomalies	• Location of seeded items • Anomaly list	100% of seeded items detected within 0.6 m halo	Met: 100% within 0.6 m
Production rate	Acreage and number of cued interrogations Pre-processing time	• Log of field work and data pre-processing time	Detection: 0.7 acre/day Cued mode: 100 anomalies/ day. Pre-processing time <3 min per target	Not met: Detection @ 0.5 acre per day. Not met: Cued mode: 60 and 86 anomalies/day. Not met: 3 min/ target
Analysis and Classification Objectives				
Maximize correct classification	Number of TOI retained	• Ranked dig list • Scoring reports by IDA	Approach correctly identifies the presence of 95% of TOI	Met: 96% of the TOI were correctly classified
Maximize correct classification of non TOI	False alarm rate (FAR)	• Ranked dig list • Scoring reports by IDA	Reduction of clutter digs by 40% for 95% TOI	Met: Reduction of clutter digs by 41% at 95% TOI digs
Minimize number of unclassifiable anomalies	Number of "Can't Analyze" in cued data classification	• Ranked dig list	Reliable classification parameters for at least 90% of dig list	Met: 95% reliable
Correct location and depth of TOI	Accuracy of estimated target parameters for seed items	• Results of intrusive investigation • Predicted location	$\sigma Z < 0.10$ m σN and $\sigma E < 0.15$ m	$\sigma Z < 0.10$ m σN and $\sigma E < 0.15$ m (discarding frag pits)

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3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION

Dynamic detection survey should cover a maximum of the area of interest so that all detectable targets are illuminated. Targets are detectable if the transmitted field is sufficiently strong to reach the target and if the measured target response is sufficiently strong in return to exceed a given threshold. Simulations and analysis of field data suggest that there is negligible loss of detect-ability when a target is located 10 cm to the side of the MPV.

3.1.1 Metric

The footprint of MPV detection survey is compared with the surface area for the region to be studied in dynamic detection mode.

3.1.2 Data requirements

The geographic coordinates for the perimeter of the region to be surveyed and the MPV survey track is utilized.

3.1.3 Success criteria and result

Success is met with 99% spatial coverage with 0.7 m footprint in the open field area, where GPS allows verification. The same performance is obtained in the dense forest, according to the positioning system used in that area, not accounting for parts that could not be surveyed due to flooding or major obstruction from tree aggregates and large boulders. The survey track is shown in Figure 3, with the open field area on the East side (lines going E-W) and the forest on the West side (lines N-S).
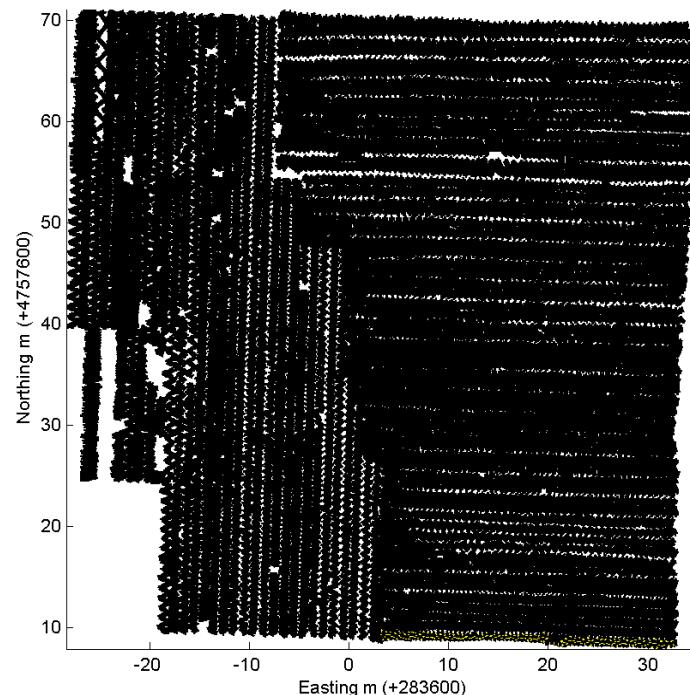
Figure 3.   Spatial Coverage for MPV Dynamic Survey (survey track)

3.2   OBJECTIVE: STATION SPACING IN DETECTION MODE

This objective is meant to ensure that the target response is not being smeared out by an operator moving the sensor head too fast.

3.2.1   Metric

The distance between soundings along lines is computed.

3.2.2   Data requirements

The sensor head location is derived from GPS and AHRS measurements.

3.2.3   Success criteria and result

Success is met with 85% of the data points having at most 0.1 m spacing along line and 95% having at most 0.15 m spacing, as shown in Figure 4.
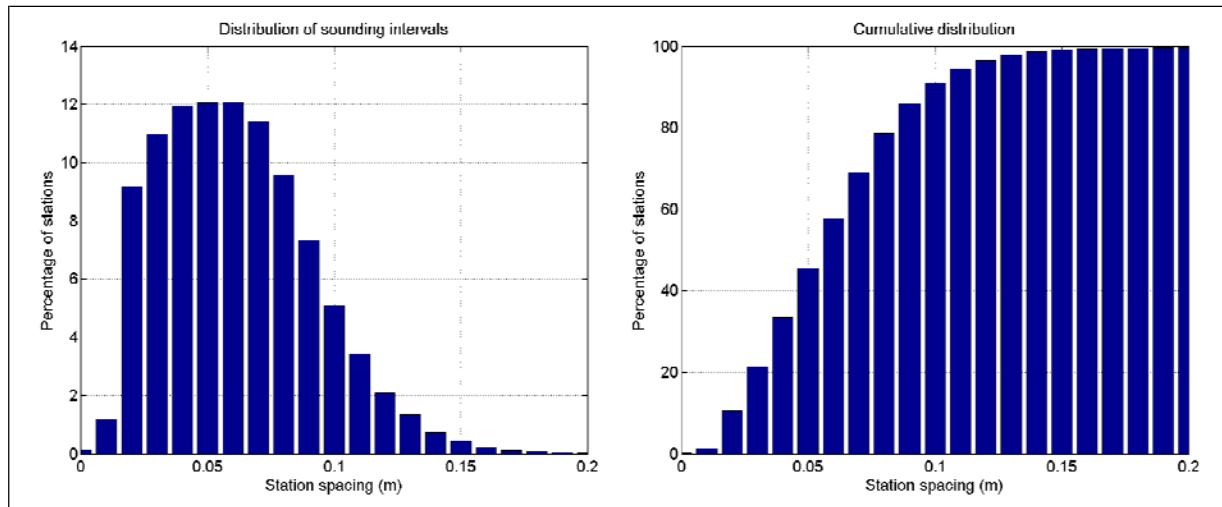
Figure 4.   Distribution and Cumulative Distribution of the Separation between Consecutive Measurements

3.3   OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS

Reliability of survey data depends on the stability of survey equipment. This objective concerns twice-daily verification on a test strip where metallic targets are buried. The IVS is surveyed in detection mode during the detection survey. The IVS targets are surveyed in cued interrogation during the entire demonstration.

3.3.1   Metrics

The metric for detection relates to the amplitude of the maximum target response, defined as the norm of the total field on each receiver cube for the 0.5 ms time channel. The metric for cued interrogation is the target size, here defined as the norm of the polarizability components also for the 0.5 ms time channel.

3.3.2 Data requirements

IVS data are recorded for both detection and cued survey modes. A detection map is built and the detection amplitude is computed for each target. For the cued survey the data are inverted and the stability of the recovered target parameters is verified.

3.3.3 Success criteria and result

The detection requirement is a factor 2 uncertainty on the target response, which corresponds to the signal variation for a 5 cm increment in depth or lateral offset between the sensor and buried object. The criterion is met with a factor better than 1.5 after four dynamic passes over the three items buried in the IVS. The objective for cued interrogation is a factor 1.5 on the target size parameter. The objective is met (see section 7.3).

3.4   OBJECTIVE: CUED INTERROGATION OF ANOMALIES

The reliability of cued data depends on acceptable instrument positioning during data collection in relation to the actual anomaly location.

3.4.1 Metric

The metric for this objective is the percentage of anomaly peaks that are located within the acceptable distance to the center of the cued interrogation survey of each anomaly.

3.4.2 Data requirements

The demonstrator records the location of their instrument for each cued anomaly interrogated and verifies that the anomaly is covered by the survey pattern. Verification is done while still on site so that anomalies can be re-acquired if needed.

3.4.3 Success criteria and result

The objective of centering the survey pattern within 50cm distance of the actual anomaly location for 100% of the cued anomalies is met.

3.5   OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

Quality data should lead to high probability of detecting all TOI at the site.

3.5.1 Metric

The metric for this objective is the percentage of seed items that are detected using the specified anomaly detection threshold.

3.5.2 Data requirements

The demonstrator produces a detection list that is submitted to Amy Walker at USACE, Huntsville for evaluation.

3.5.3 Success criteria and result

The objective is met if 100% of the seeded items are detected within a halo of 0.5 m.

3.6 OBJECTIVE: PRODUCTION RATE

This objective concerns data collection and pre-processing time.

3.6.1 Metric

The metrics for this objective are the mean daily survey rates in terms of acreage for dynamic survey and number of targets for cued interrogations, and the mean pre-processing time per anomaly.

3.6.2 Data requirements

The acreage and number of surveyed anomalies and the pre-processing time were recorded on every day.

3.6.3 Success criteria and result

The initial objective was to achieve mean daily survey rates of at least 0.7 acre and 100 anomalies, and if pre-processing time is less than 3 minutes per selected target. The survey set up was initially delayed due to some sensor issues. These issues are discussed in a separate section.

The detection survey rate was purposely reduced to 0.5 acre, or 1 acre in two days, to account for the heavy equipment load and somewhat awkward ergonomics for the crews. The mean cued interrogation rate was different for the open field and the forest: 86 anomalies per day in the open and 60 per day in the forest. The standard pre-processing time for cued interrogation data was approximately 3 minutes.

3.7 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

This is one of the two primary measures of the effectiveness of the classification approach. By collecting high-quality data and analyzing those data with advanced parameter estimation and classification algorithms, targets were classified with high efficiency. This objective concerns the component of the classification problem that involves correct classification of TOI.

3.7.1 Metric

The metric for this objective is the number of items on the anomaly list for a particular sensor that can be correctly classified as TOI by each classification approach.

3.7.2 Data requirements

Each demonstrator prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used their scoring algorithms to assess the results.

3.7.3 Success criteria and result

The objective are considered to be met if 95% of the TOI are correctly labeled as TOI on the ranked anomaly list. There were 70 TOI among the 129 anomalies that were classified and scored by the MPV and for which there was ground truth. Although three anomalies were missed, the objective was met with 96% correct classification of TOI.

3.8 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

This is the second of the two primary measures of the effectiveness of the classification approach. By collecting high-quality data and analyzing those data with advanced parameter estimation and classification algorithms, targets were classified with high efficiency. This objective concerns the component of the classification problem that involves false alarm reduction.

3.8.1 Metric

The metric for this objective is the number of items on the sensor dig list that can be correctly classified as non-TOI by each classification approach.

3.8.2 Data requirements

Each demonstrator prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used their scoring algorithms to assess the results.

3.8.3 Success criteria and result

The objective are considered to be met if more than 40% of the non-TOI items can be correctly labeled as non-TOI while retaining at least 95% of the TOI on the dig list. There were 34 false alarm digs out of 59 non-TOI items.. The objective is just met with 42% rejection for a site where 70 of the 129 anomalies were due to TOI.

3.9 OBJECTIVE: MINIMUM NUMBER OF UNCLASSIFIABLE ANOMALIES

Anomalies for which reliable parameters cannot be estimated cannot be classified by the classifier. These anomalies must be placed in the dig category and reduce the effectiveness of the classification process.

3.9.1 Metric

The metric is the number of anomalies that cannot be analyzed by our method.

3.9.2 Data requirements

The submitted dig list specifies those anomalies for which parameters could not be reliably estimated.

3.9.3 Success criteria and results

The objective is met if at least 90% of the cued anomalies can be analyzed. Here 95% of the anomalies were classified.

3.10 OBJECTIVE: CORRECT ESTIMATION OF LOCATION AND DEPTH

Correct target classification relies on the capability to extract valid target parameters. Accurate TOI location is also important for safe and efficient site remediation.

3.10.1 Metric

The metric is the difference between observed and predicted depth and geographic location.

3.10.2 Data requirements

Target location and depth are recorded and compared to ground-truth validation measurements.

This objective requires accurate ground truth.

3.10.3 Success criteria and result

Depth should generally be predicted within 0.10 m and geographic location within 0.15 m. An exception can be made for frag pits, which cause challenges for both the predicted and recovered locations and depths. We find that the depth was predicted within 0.10 m for 80% of the TOI and 100% of the TOI when discarding frag pits. The geographic location error could only be compared in the open field. We find that there was a bias of 0.1 m in Easting relative to the ground truth. Correcting for that bias all field TOI were predicted within 0.15 m of the ground truth location.

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4.0 SITE DESCRIPTION

4.1 SITE INFORMATION

The demonstration site is located at the Shooting Field at NBAFS, New Hampshire. For a detailed description of the site, please refer to the *ESTCP Munitions Response Live Site Demonstrations, New Boston Air Force Station, NH, Demonstration Plan* (ESTCP, 2013). The primary areas of interest for the dynamic and cued MPV study covers one acre and is located in grid J22, as depicted in Figure 5.
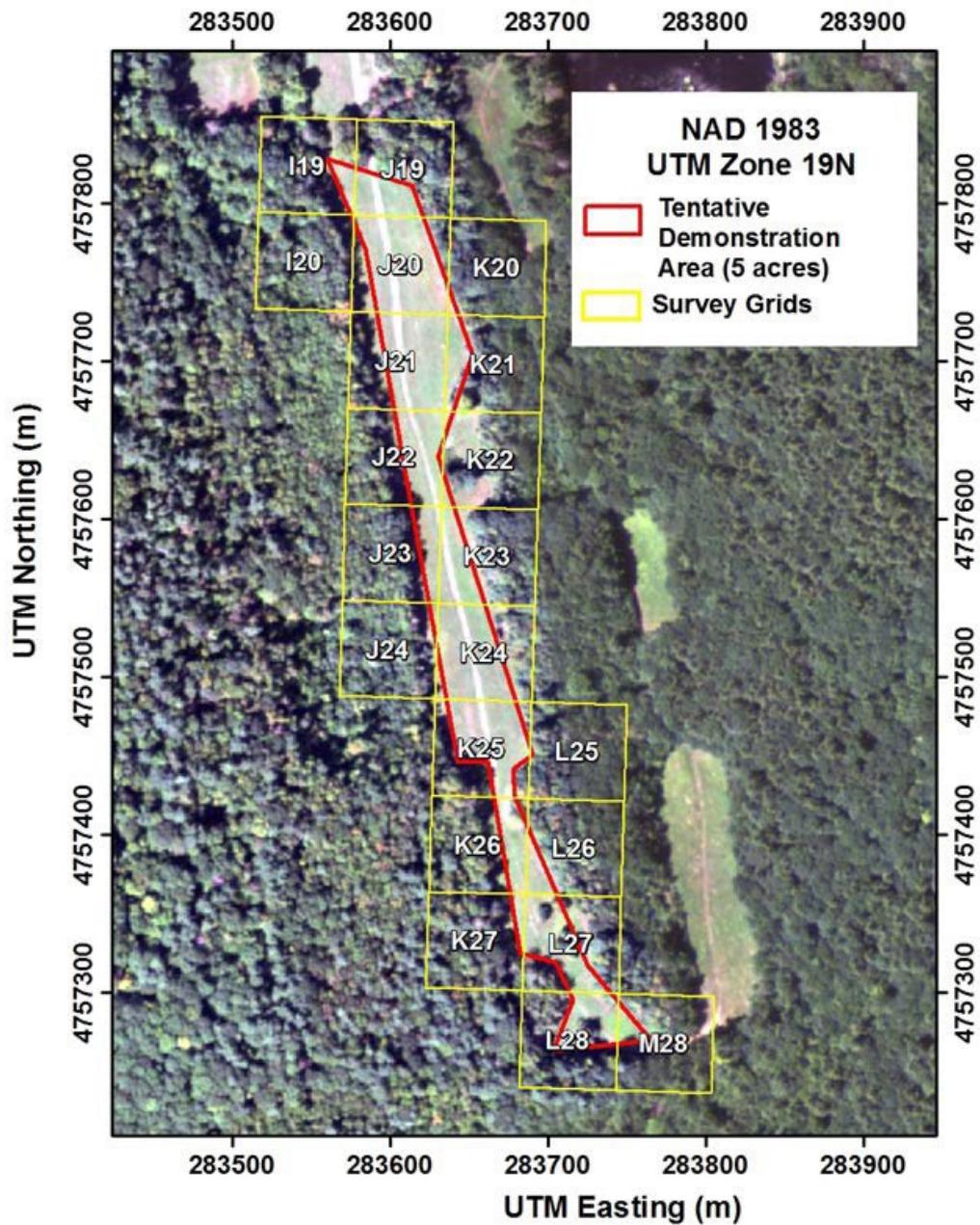
Figure 5.   MPV Study Area in Grid J22 at NBAFS Shooting Field

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4.2   MUNITIONS CONTAMINATION

The ESTCP study area MU705 was one of the primary bombing/aerial targets used at NBAFS from 1942 to 1956. Unserviceable tanks, trucks, and half-tracks were used as strafing targets for machine guns, 20-mm cannons, and rockets. MEC anticipated to be present at MU705 are as follows:

- 20mm Projectile, Target Practice;
- Practice Rockets, 2.25-inch and 5-inch;
- HE Rockets, 5-inch;
- Practice Bombs, 3-lb, 4.5-lb, 100-lb, 500-lb, and 1,000-lb;
- General Purpose HE Bomb, 100-lb;
- HE Depth Bomb, 325-lb and 350-lb;
- M69 Incendiary Bomb;
- Photoflash Bomb, M46; and
- Practice landmine (supplied as training target for the test pit and added to the TOI list for classification).

5.0   TEST DESIGN

The goal of the study was to demonstrate detection and classification with the MPV at a site with dense forest, small targets and extremely high target density, and to characterize performance in terms of the derived data products and the field usability.

5.1   DEMONSTRATION SCHEDULE

The initial scope was to survey one acre of open field and forest and interrogate approximately 250 anomalies. The first day was dedicated to preparing the survey and getting acquainted with the site and training the crew to operate the instrument by acquiring calibration measurements in cued and dynamic modes on a test pit and IVS. The detection survey lasted 2 days, during which the data were almost immediately analyzed and reviewed by a geophysicist on site.

A detection strategy was derived from analysis of the local site conditions. A list of anomalies for the open field and for the forest was submitted to the ESTCP Program Office and to Amy Walker from the USACE in Huntsville, who indicated which anomalies should be interrogated in priority. The original objective of interrogating 250 anomalies was revised and almost 500 anomalies were selected.

Quality control and data pre-processing of detection and cued interrogation data were performed during the deployment to ensure that sufficient data were acquired to cover the survey area and to characterize individual anomalies. In depth data analysis and classification were performed after the deployment. Predicted target locations were quickly supplied to the ESTCP to facilitate the UXO clearance effort, whereas the classification ranked dig list was submitted at a later stage, once some local ground truth information became available.

5.2   SYSTEM SPECIFICATION

5.2.1   Data acquisition

For cued interrogation mode the system is set for 25 milliseconds (ms) excitation and 25 ms recording of EMI transients. This is accomplished by using 0.9 seconds (s) data blocks that include 9 repeats (100 ms per cycle). Station time is set to 6.3 s by stacking 7 data blocks (effectively 9 x 7 = 63 cycles are averaged). The data are recorded with 133 logarithmically-spaced time gates (5% gate width) from 0-25 ms. Dynamic survey is set with 2.7 ms time window and short 0.1-s data block so as to reduce smearing of the signal by sensor motion.

5.2.2   Positioning and navigation

The dynamic area has open sky and positioning was based on the GPS. In cued mode, local positioning was achieved with the beacon system, though the GPS data were still recorded to verify beacon accuracy whenever enough satellites were visible, in particular at the IVS and in the open- field area. The GPS was a Trimble R8 that was mounted on the opposite end of the MPV handling boom. The GPS was also used to locate pre-programmed flag locations. An XSens MTi orientation sensor was mounted near the GPS to measure azimuth. The three-axis sensor data are also used for verifying the pitch and roll inferred from the beacon measurements.

The beacon boom was laid on the ground within 2 meters of the survey flag. Boom orientation was recorded with a secondary XSens orientation sensor that was mounted at the boom center. The boom was generally oriented in the North-South direction on the East side of target. After data processing, beacon-derived positions were located relative to the local flag and geographic North, and subsequently globally-referenced using the supplied GPS coordinates of each flag.

5.3 CALIBRATION ACTIVITIES

Calibration is designed to verify correct sensor operation and calibrate the recorded sensor response over known targets. A sample set of the expected targets were calibrated with test pit measurements. Each sample was successively placed inside a clutter-free training pit and surveyed in cued interrogation mode. A minimum of four different orientations and one depth per target were acquired to train feature extraction and classification methods. Data were inverted on that day to verify the stability of the recovered target parameters.

Dynamic data were acquired over a 20 mm projectile buried at 15 cm in horizontal, vertical and oblique orientation for the purpose of confirming the detection threshold procedure with empirical evidence.

The IVS was surveyed for calibration and sensor verification in dynamic detection and cued interrogation modes. The IVS was studied multiple times for training in both modes, and twice daily in the collection mode of the day for verification. The detection data were analyzed to verify spatial coverage and the stability of the EMI responses, thus providing an indirect check on the data collection procedure and on the sensor components. The amplitude of the target response were also used for calibration against the detection threshold. The dynamic data were inverted to recover the dynamic polarizabilities of the buried targets. These were used for detection simulations and classification of dynamic data. The cued data were also inverted to recover the static polarizabilities, verify their stability, and provide training data for classification.

Geologic background measurements were acquired every 10-12 anomaly by identifying "quiet" areas, which can be recognized with the arrows display in detection mode and by examining the recorded decay curves in static mode. Data were analyzed to quantify the spatial and temporal variability in background noise and detect potential soil magnetization.

5.4 DATA COLLECTION PROCEDURES

5.4.1 Detection survey

The detection survey was performed by walking along pre-defined survey lines and sweeping the sensor from side to side while keeping the sensor head parallel to the ground – the sensor track resembles an "S". Given a detection footprint of 0.7 m, we could achieve full coverage on a 1-m line spacing by sweeping the sensor with approximately 0.5-m amplitude and 0.5-m period. Station spacing depends on survey speed. Following an empiric rule such that the sensor should not move more than the receiver length (8 cm) during acquisition of a data block (0.1 s), sensor-head speed should be between 1 m/s with station spacing of 0.1 m along each of the 5 receiver-cube tracks. The resulting along-line speed is approximately 0.3 m/s.

5.4.2   Sample density for cued interrogation

Similar to previous demonstrations, cued interrogation soundings were collected around the marked target location (ground paint or flag). The first sounding was acquired at the marker. In general we followed a five-point square pattern as in Figure 6. Given that receiver cubes are separated by 0.2 m we could obtain a somewhat uniform spatial sampling with 0.6-0.7 m spacing between soundings locations.
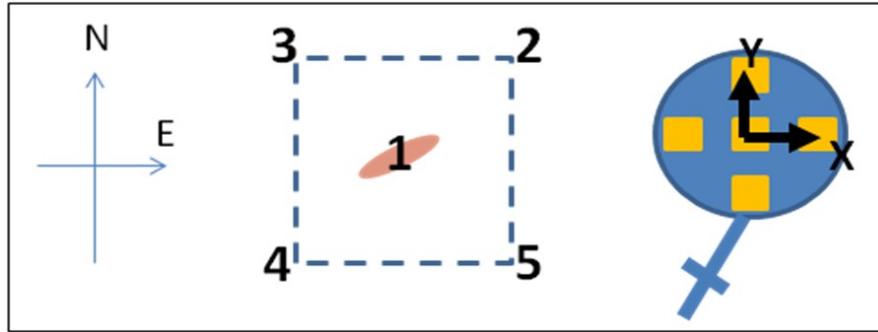
Figure 6.   Cued Survey Pattern with Five Points Centered on Marked Target Location

5.4.3   Positioning and navigation

The RTK GPS was used in open field to locate the sensor for mapping, and for re-acquiring targets for cued interrogation. The GPS data were assimilated by the DAQ to indicate, in real-time, the sensor location. Detection lines were pre-programmed to track the spatial coverage on the control display. Flagged anomalies were also preset so that the GPS could be used for navigation to these anomalies.

The forested area presented a challenge for navigation. Densely spaced trees and a thick canopy obstructed satellite view and precluded use of GPS. Therefore an alternative method was required for positioning the MPV sensor head and building a UXO detection map. The dynamic data collected at the Camp George West Demonstration showed a strong correlation between the variations in the azimuth and the cross-track position along survey lanes, where the sensor was laterally swept while moving forward. The azimuth was measured by an AHRS sensor and the position by a GPS unit. The observed correlation showed that the MPV sensor-head location could be predicted from the AHRS-recorded sensor heading without use of a GPS. The AHRS and GPS data from George West showed that the distance forward during a sweep cycle was relatively constant, more constant than the walking speed. We built a model for predicting the MPV location along and across track based on the azimuth variations and validated it with the open field data from New Boston to ensure its applicability with this project crew (Figure 7).
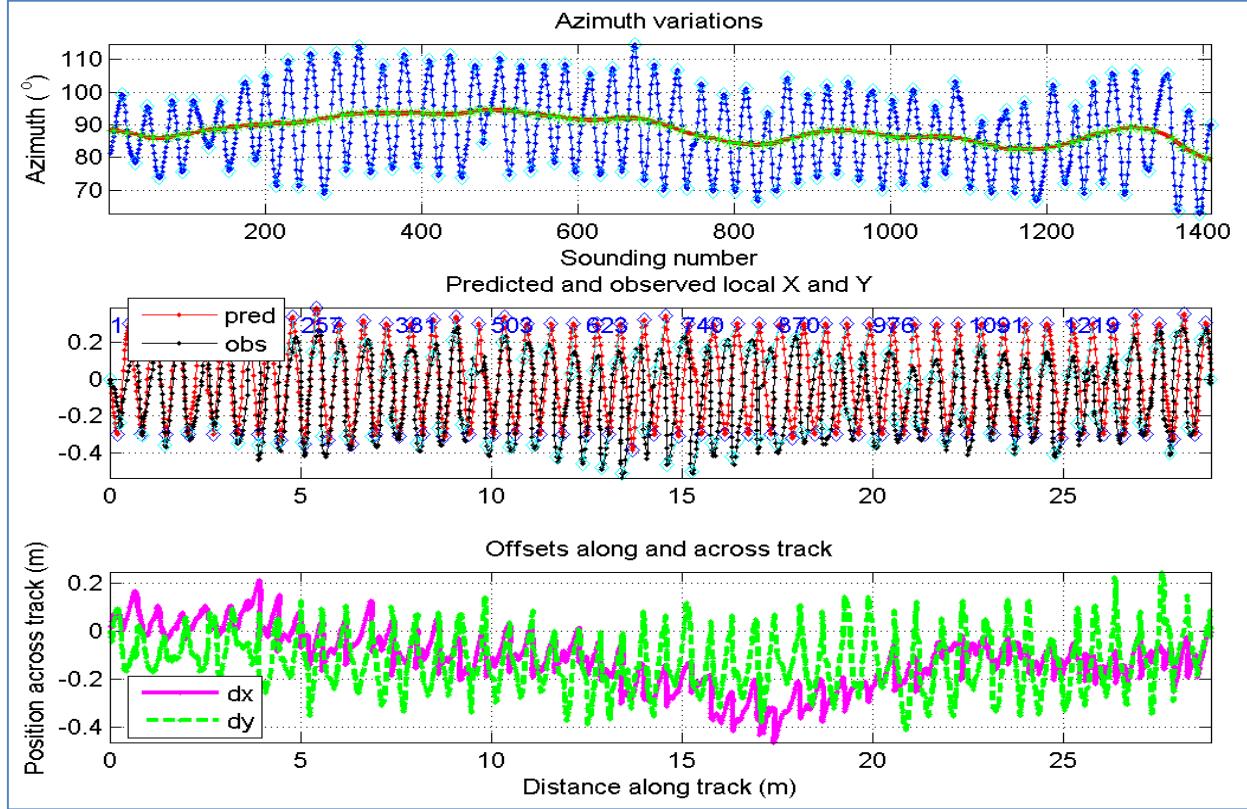
Figure 7.   Example of Prediction for the Sensor Location along Detection Lines Using Azimuth Variations

The top panel shows 140 seconds of AHRS-recorded variations over 30 meters in the open field; the center panel shows the GPS-measured (obs) and azimuth-inferred positions (pred); the bottom panel shows the positional error of the inference method (dx along track and dy across track).

The method was implemented by laying survey ropes on the ground to delineate one meter-wide sweeping lanes. The ropes stayed for the project duration to help cued re-acquisition. Lanes were defined as 15-m long segments to limit drift and positioning errors that could arise from unexpected disturbances such as trees and terrain features. The detection map was constructed by stitching all local survey segments to cover the entire wooded area, using global coordinates. The map could then be used for target picking, similar to the open-field data.

Reacquisition for cued interrogation of detected anomalies could not rely on GPS for the forest site. Instead, the field crew was supplied with a target list sheet where anomaly locations were indicated in terms of the line segment number and an estimate of the distance along track and relative position across track. These analogue indications served as a starting point for a local detection search within a 0.5-m radius to locate the peak amplitude, where cued interrogation was to take place. The peak was estimated by looking at the "dancing arrows" display and trying to have the arrows point toward the center of the sensor array. The target location was refined after collecting the five-point cued-interrogation data. The crew found that the target was generally located within 0.3 m of the starting point, which validated the accuracy of the azimuth-prediction method. A paint marker and a reference flag with an identity tag were placed at the target location to direct the digging crew.

5.4.4 Quality checks

General check on proper operation was verified every time the instruments were powered on. The positioning systems were checked by waving the MPV head and verifying on the screen display that the reported position and orientation numbers as well as the location map were being updated and vary as predicted. The EMI elements were checked by acquiring data in dynamic or static mode, depending on the stage of the project. The operator verified that the "dancing arrows" display was updated in response to variations in the EM environment, that signals were appearing in the signal time-decay display (Figure 8) and that a file was being written.

Battery change was accompanied with a basic system check although the DAQ was not necessarily shut down (hot-swap of the batteries). A background soil measurement and an in-air measurement were acquired in the current survey mode (dynamic or static) before and after the battery swap. The operator checked the display for anomalous behavior. The data were later examined on a workstation to identify any sensor drift. In addition, background measurements for the soil response, with the sensor on the ground, and the in-air response were acquired every 10-12 anomaly. The former test was to document potential variability in the soil response and ensure that the most relevant background was applied – a magnetic soil response would mostly affect the late time data and may appear similar to the presence of a large deep target. The in-air measurement was designed to capture the intrinsic sensor response as a function of the battery power, which varies as the battery drains out. That response is particularly important at early time, during the 0.3 ms after the transmitter turns off, when a large inductive response is observed in the Z-component receivers due to their coupling with the Z-axis transmitter (the so-called "transmitter ringing" effect).

Dynamic acquisition was continuously monitored by verifying that the sensor location map, the positioning data table and the dancing arrows were being updated. In particular, the map would show a sensor track that covered the survey line without any gaps; a pop-up window would appear if data errors were encountered; the dancing arrows should move around in response to changes in the sensor clearance or the presence of metallic objects. The second operator, who carried the backpack, was also involved in quality control by verifying that the front operator was keeping the sensor head close to the ground, covering the entire line and keeping a somewhat uniform pace.
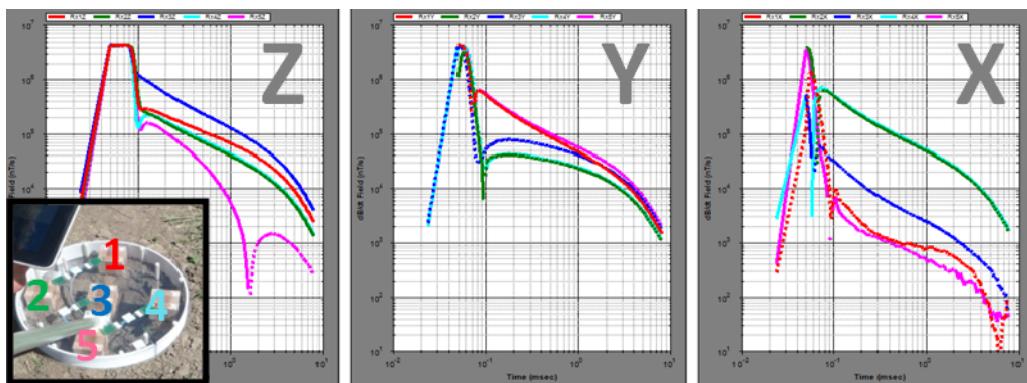
**Figure 8.   Typical Target Response when the MPV Head is Placed Directly above a Buried Target**

The Z-component data shows that target is closest to the center cube (#3) and equally distant from lateral cubes 2 and 4, while signal in cube 5 resembles background. The Y data confirm that target is buried between front and back cubes (1, 5) and X data confirm that target is located between side cubes 2 and 4.

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Cued interrogation followed a specific protocol. Each sounding was displayed immediately after acquisition to verify proper sensor operation and correct characterization of the buried target. The operator verified that receivers were properly operating by examining data decay curves (Figure 8) and the "dancing arrows" display. Any abnormal sounding would be deleted, reacquired at the same location and flagged in field notes to differentiate it from acceptable soundings. If receiver failure occurred the survey would be stopped until a solution was found. Correct characterization of an anomaly followed a series of steps:

- The first sounding required particular attention to verify that the signal source originated right below the marked location. There can be an offset between the picked anomaly location, where the MPV would be placed, and the apparent target location that is predicted by the current MPV data – this can arise from positional error, choice of a target picking algorithm, or the presence of multiple targets. In case of large apparent offset the operator was expected to try and interpret the cued interrogation data to locate the signal source and acquire additional soundings if necessary;

- Anomaly coverage was verified by ensuring that the furthest receiver was measuring background. If residual signal from the target remained then additional soundings were collected to ensure full coverage of the anomaly spatial decay. For instance, if the MPV front receivers showed above-background signal when the MPV was placed in position 2 of Figure 6, then a sounding was to be collected North of the middle of positions 2-3. If a nearby, interfering target was detected while being un-flagged for cued interrogation, then supplementary soundings were acquired to improve characterization of the two sources.

Beacon positioning was verified against the GPS-AHRS combination in the open field by comparing the predicted sensor head location. The integrity of the beacon method was maintained by ensuring that the data acquisition system (DAQ) remained at least 2 m away from the beacon boom and by monitoring of the beacon signal amplitude, which can also be displayed on Figure 8.

Off-site data quality review was performed on a daily basis by importing dynamic and cued data. The geophysicist loaded up the data to verify that positioning and EMI sensors were properly functioning, that noise levels were normal, that positioning systems (GPS and beacon) yielded realistic positions and that spatial coverage was sufficient. In particular the geophysicist checked for gaps in the dynamic detection map, and verified that anomalies were fully covered in cued mode. If problems occurred then causes were investigated and the affected survey lines or anomalies were resurveyed if necessary.

The last check was verification that all targets had been visited. In the open field we kept track of all anomalies by having pre-programmed their GPS coordinates and displaying their location on the sensor display map. Each visited target was automatically marked on the map. In the forest we used manual field notes and a spreadsheet to keep track of the number of anomalies per line and make sure that all anomalies were visited.

5.4.5 Data handling

Data were stored as .tem files on the DAQ and converted to .csv files before every battery change. We kept a copy of all .tem and .csv files on the DAQ, on a portable hard-disk drive and on the field laptop that was used for reviewing the data.

The back operator documented the survey by noting target names and file numbers in addition to any remarks made by the principal operator. Field notes were digitized every day by taking pictures of the notes and filling out a spreadsheet that was used for pre-processing.

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6.0   DATA ANALYSIS

6.1   PREPROCESSING

The DAQ recorded data streams from the sensor head, beacon receivers, attitude sensor and GPS. Each static sounding or segment of a line search was saved into a .tem binary file, which was later converted to a .csv file. Several pre-processing stages were performed before delivery to the analysts.

6.1.1   Positioning

The open field dynamic data were merged and the AHRS and GPS data were combined to predict the receiver-cube locations. In the forest the AHRS azimuth was used to predict the MPV location, as described in a previous section.

The beacon receiver data, transmitter current and attitude measurement were combined to infer the MPV head location. When GPS Q factor was equal to 4, GPS and attitude readings were combined to predict sensor head location and compare to the beacon. Discrepancies were resolved using field notes; otherwise soundings were discarded.

6.1.2   Normalization and data delivery

The EMI data were divided by the maximum transmitter current amplitude to normalize the response to a unit transmitter excitation, hence compensating for fluctuations in transmitter battery power. Background measurements were analyzed to define the background response to be subtracted from the cued data. The resulting data were visually validated.

In cued mode each sounding generated an individual data file. Files were subsequently combined to a single record for each target, comprising of a data block for each sounding with the sensor location and attitude, sounding number and field comment. Only validated soundings were included. The final file name included the sensor and target names following ESTCP naming instructions. Files were posted on a ftp server for distribution to analysts.

6.2   TARGET SELECTION FOR DETECTION

Dynamic survey data were assimilated, filtered and interpreted to produce a digital map of the area and identify anomalies that require further investigation. Anomalies were retained when their signal amplitude exceeded a given threshold. That threshold was derived from numerical simulations of the worst case scenario for the expected targets and validation with empirical data that were collected on site, similar to the approach that was employed at Camp George West. A relatively late time channel at 1.4 ms was chosen as a means to wean out fast-decaying clutter while remaining above the background noise amplitude. The Z-component data were used for target selection, as the Z-data has maximum Signal to Noise Ratio relative to the horizontal component data and the vector norm (total field).

The first condition for an anomaly to be selected is for the amplitude of the EMI response at that location to significantly exceeded the variability of the background noise.

Common practice is to require that the signal be larger than 5 times the standard deviations of the background noise (after the signal has been de-median filtered). The background noise statistics were analyzed for the field data acquired in the open field and in the forest (Figure 9A), where similar characteristics were observed. The standard deviation was estimated to be 0.2 mV/A for the 1.4 ms time channel, which put the detection threshold at 1 mV/A. Dynamic data were acquired by sweeping the MPV sensor head over a test pit where 20 mm projectiles and 20 mm simulants were buried at 20-25 cm depth in various orientation. We found that the maximum signal over the buried target exceeded that threshold (Figure 9B). The detection threshold at 15-cm depth was confirmed by simulations, where the worst case scenarios were investigated by varying the sensor and target offset, the target azimuth and inclination, as well as introducing variations in ground clearance and in the sensor attitude. We found that if a 20 mm projectile was placed in horizontal orientation at 15 cm depth within the sensor footprint (50 cm diameter), there is a 95% probability that the signal is above 1 mV/A and an ~100% probability that it will be above 0.5 mV/A.

A.   **B.**
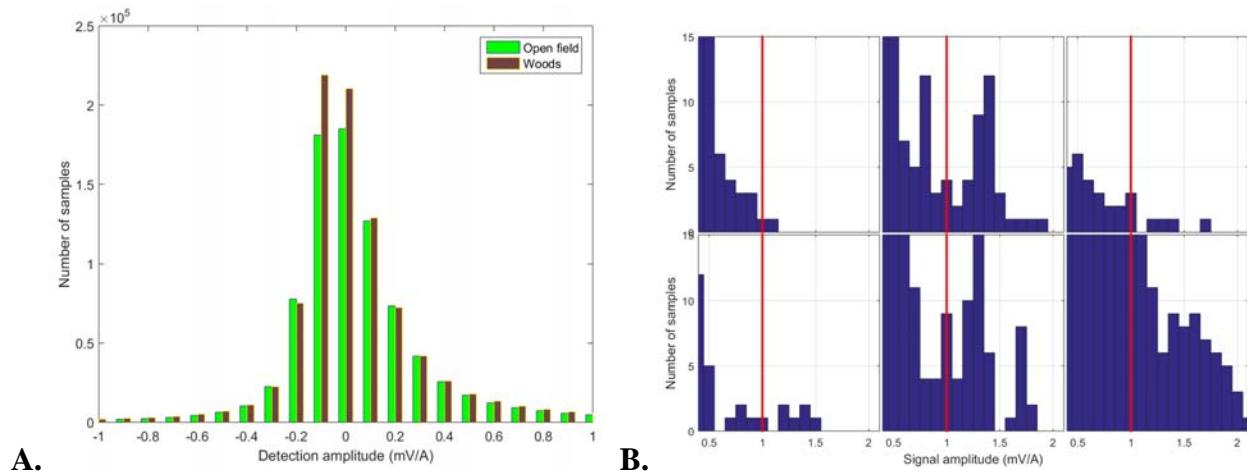
Figure 9.   Target Detection Process Based on Site-specific Data

A: Background noise distribution for the 1.4 ms time channel in the open field and in the forest. B: Signal amplitude vs. number of data samples for 6 tests where a 20 mm projectile or simulant was buried in a test pit at a depth of 20-25 cm. The red line indicates the proposed detection threshold.

The Z-data for each cube were used as an independent survey line with an algorithm that picks targets along line profiles and keeps anomalies for which there are at least two consecutive data points exceeding the threshold. The line profile algorithm was preferred to the gridded image detection method because the latter is more sensitive to positional error and data gaps, which can create grid artifacts. A detection list with geographic locations and anomaly labels was submitted to the ESTCP Program Office and to Amy Walker from USACE Huntsville, who acted as data quality officer for the project. To account for the fact that valid TOI would have a certain spatial footprint and appear on multiple consecutive points or multiple receiver lines, the number of measurements that exceeded the threshold within a 0.2-m radius was utilized to categorize detected anomalies. A high priority label was given to the anomalies that could be TOI and should be retained for cued interrogation, and a low priority documented raw detection events (data spikes, small nails and other negligible metal scrap). In that manner, the entire list documented the intrinsic detection capability of the system, while the high priority illustrates an attempt of data-based pre-screening.

6.3   PARAMETER ESTIMATION

As in previous ESTCP demonstrations, data analysis was performed within UXOLab, a MatLab-based research software developed by BTG with the University of British Columbia in Vancouver. Data were inverted using a three-dipole instantaneous polarization model (Pasion and Oldenburg, 2001). The target polarizability decay parameters are the main features for the ensuing classification. Inversion setup parameters such as noise estimation are generally decided upon examination of training pit data and noise estimates on the IVS and in the field. Solutions with one or multiple targets are generated for every selected target. Decisions regarding the number of targets at a given location are made through statistical classification by prioritizing the most munitions-like solutions.

Inversion results are reviewed by an experienced geophysicist to identify any potential issues with the inversion setup or with the data, and select data subsets as required for fitting all detected anomalies (masking).

6.4   TRAINING

Statistical classifiers are trained on a library of target features that has been accumulated during the previous surveys and new features associated with local targets. Measurements collected over the training pit provide that local information. Munitions are studied at various orientations so that their parameter variance can be estimated.

After testing of the classifier, additional training data may be requested to the ESTCP to obtain information about particular targets. Targets may be remarkable because there they belong to a cluster of unknown targets with similar features. Targets may stand out for having particularly large inferred size. This process of requesting training data is iterated until sufficient confidence in the classifier is attained.

6.5   CLASSIFICATION

As for past ESTCP demonstration studies, the following guiding principles were applied:

- *Selection of features:* By analysis of the training data, those features that contribute to separation of the different classes (comprising UXO types and clutter) are selected. Our experience shows that the three sets of instant polarizability decays generally yield successful classification with the MPV (and other sensor data). The data are inverted in different manners, using single-target and multiple-target inversions and eventually different noise parameters or mask sizes. Therefore multiple sets of features can be extracted from the same anomaly and the model that most likely resemble a TOI is automatically selected through classification;

- *Choice of classification algorithm:* Methods are elaborated through analysis of the training data. Past studies have been successful using a Library Fit method or a Support Vector Machine (SVM) classifier. These methods can be combined or applied multiple times with different parameters;

- *Number of UXO-classes or reference items*: A library of reference items found in previous studies is augmented with local items measured on a test pit at the site. The library includes polarizability decay curves that are intrinsic to each library item. The reference library is reduced by retaining the expected targets of interest in addition to reference items for which there is a close match with polarizabilities in the field data;

- *Classification:* Anomaly labels are placed in a prioritized dig-list by using the classifier to compute probabilities of class membership for unlabeled feature vectors. The most likely TOI is reported in the dig sheet.

The classification approach was finalized after examination of the recovered target parameters and analysis of local conditions. A ranked anomaly list was prioritized according to the likelihood of being UXO and formatted as in Figure 10. The first items on each anomaly list were those targets for which reliable parameters could not be extracted and therefore had to be dug. Next were the items that were considered as "high confidence' munitions, ranked according to decreasing confidence that the item was hazardous. Any items that were analyzed without reaching an unambiguous classification decision were placed next on the anomaly list. Finally, all items that were confidently classified as non-hazardous were ranked by their confidence.

Figure 10. **Format of Prioritized Anomaly List to Be Submitted to ESTCP Program Office.**

7.0   PERFORMANCE REVIEW

7.1   DAQ SOFTWARE ISSUES

The study was marked with problems with the integration of the AHRS sensor units due to software modifications since the demonstrations at Spencer Range and Camp George West. The MPV DAQ was used for experimentation with others sensors that required changes to the EM3D software and to the communication protocols with the AHRS and GPS sensors. Unfortunately, the DAQ could not be returned to its working Camp George West state. The MPV manufacturer G&G Sciences prepared the MPV sensor for the New Boston demonstration but the short mobilization notice left limited time for testing the stability of the system before the field study. The first assembly tests showed that the AHRS sensor data would not be reliably assimilated by the EM3D software: the AHRS sensor would appear to turn itself off at random times during acquisition or when switching between acquisition modes. The orientation sensor information is critical for data collection and interpretation as it defines the sensor head location relative to its GPS and to other referenced locations. These issues had to be resolved before data collection could proceed, and this required altering the EM3D software. The equipment was brought back to the hotel, where a stable internet connection could be established, for the sensor manufacturer to remotely log on to the DAQ while the PI was demonstrating the instability problems. The first fix allowed some data to be collected with the AHRS but required the beacon boom to be plugged in to the DAQ, which was inconvenient for dynamic data collection. Several dynamic lines were collected nevertheless for the purpose of obtaining data to characterize the site in terms of noise and anomaly density. The PI and sensor manufacturer worked on a second fix that allowed collection dynamic data with the AHRS without the inconvenience of keeping the beacon boom connected. This workable version of EM3D was obtained at the cost of losing two days of data collection.

This configuration was used to collect dynamic and cued data for the remaining of the study. However, the software kept some instability that affected the data quality for both AHRS sensor units. During navigation in open field, any orientation issue would be detected on the control display map, where updates of the sensor location and relation to flag location would show conflicting information. Therefore the AHRS data for the MPV head was reliable for open field measurements. The situation was different in the forest, where the GPS was not available for navigation and classification. Navigation to picked anomalies was based on reported line numbers and distance along line, refined using the "dancing arrows" to locate the source location and place the first sounding. In this process, a malfunction of the AHRS units could only be noticed by verifying that the AHRS sensors were activated and that measured angle were updating in the data table screen, as recommended.

Some data quality issues could only be detected in post survey analysis, which revealed that (1) the AHRS unit on the MPV could freeze and the software would keep the same recorded value, and (2) the beacon boom AHRS readings could drift between measurements while the beacon boom had remained stationary. The first issue was the most serious because the sensor heading is critical to derive the location of the MPV side receivers (4 out of 5 cubes) relative to the center of the sensor head. The absence of reliable measurement for the roll and pitch was less of a concern, since these parameters were derived from the EMI beacon data when inferring the location of the center of the MPV relative to the beacon boom.

The absence of reliable AHRS data for the beacon boom was also an issue when using the beacon positioning. The beacon boom azimuth is needed to orient the cued locations relative to the MPV sensor. An error in the beacon boom azimuth would create a bias that would rotate the receiver locations for all soundings associated to a boom location by the same amount. Drift of the beacon boom sensor was difficult to notice in the field and required operators to pay close attention to the software interface to detect rapidly changing angles.

Issues with the AHRS sensors affected a large portion of the anomalies acquired in the forest. Some of these issues could be somewhat mitigated by post processing. An alternative formulation of the data inversion problem was attempted to salvage the data for these anomalies instead of simply qualifying them as "cannot analyze". Where the heading was missing for each sounding, the method consisted of solving for all the target parameters plus the sensor azimuth of each measurement and selecting the model that would fit the observed data and best fit a 20 mm projectile. Given that the crews had been instructed to align the beacon receiver boom and the MPV sensor head with the direction of the lines, facing North, the optimization problem was solved under the assumptions that the sensor azimuth had minimal deviation from the North. When only the beacon boom heading was missing, the same bias equally affected all soundings, so the inverse problem consisted of finding the target parameters plus a constant azimuth offset and seeking the best fit to a 20 mm projectile.

7.2   PRODUCTIVITY

The first day in the field consisted of obtaining the right of entry to the AFS, unpacking, fixing a connector damaged during travel, assembling the sensor and testing it. On the second day IVS tests in dynamic and static mode were performed. The EMI response for test items that could potentially be found on site were measured on a test pit. Dynamic data were collected in the open field despite the inconvenience of carrying the beacon boom. The following day was spent off site, testing and troubleshooting issues with the DAQ software. At the end of that day the configuration was deemed to be sufficiently stable for data collection. The next day had torrential rain allday.

The dynamic data collection over the 1-acre study site was covered in two days. This included survey in the forest, which constitutes approximately one half of the study area, and where short 15- m lines were collected to limit positional errors.

The cued interrogation data was split in two parts. The open field study covered 259 anomalies that were collected over the course of 3 days, including half a day of training with the PI, plus 22 recollects on the last day. The forest area had 238 cued interrogations over 3.5 days, plus 14 recollects on the last day. Survey in the forest was slower because navigation to anomaly locations was based on approximate distance indications that had to be refined with dynamic search. A total of 497 anomalies were investigated. The location of the interrogated anomalies and of intrusive investigations are shown in Figure 11. Cued classification was performed on the 149 anomaly locations for which ground truth was available.
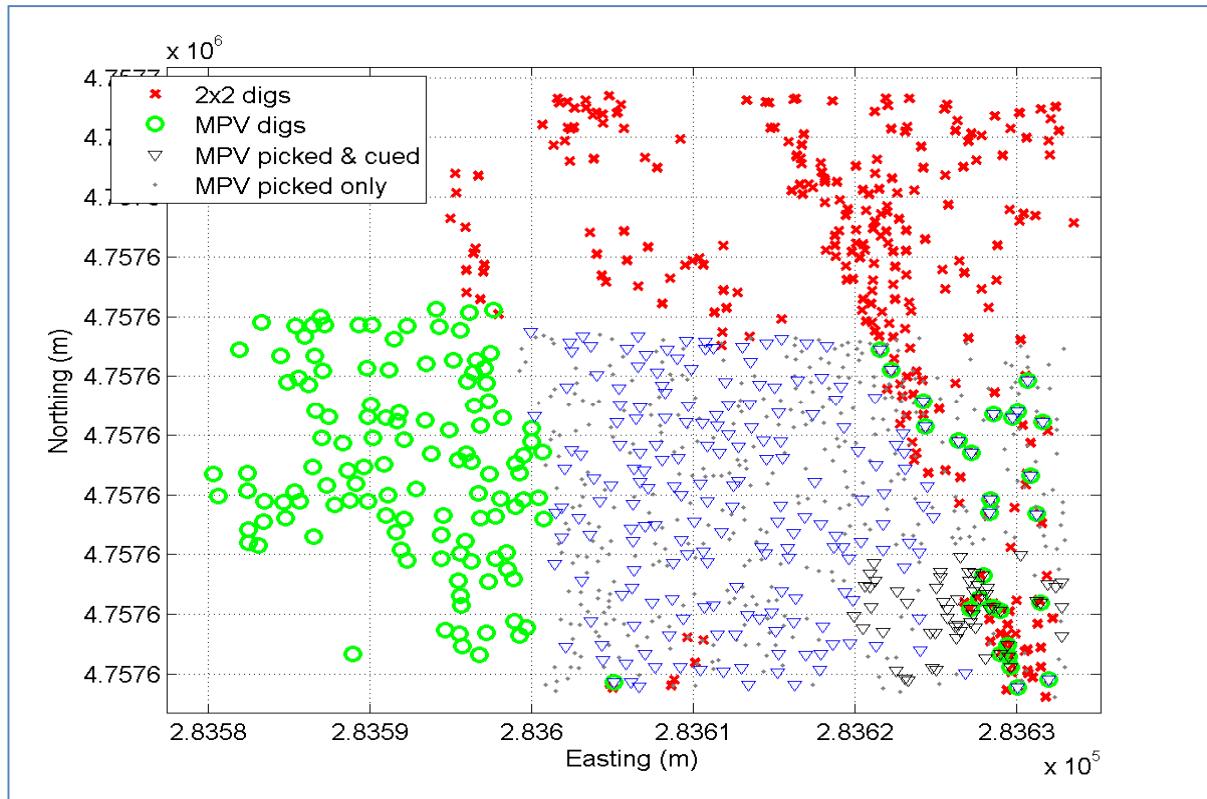
Figure 11.   Target Picks, Cued Interrogations and Ground Truth Locations

All "MPV digs" correspond to locations that were picked in the MPV detection data and cued by the MPV prior to digging. Similarly, "2x2 digs" were picked and cued by TEMTADS 2x2 sensor.

7.3 IVS REPEATABILITY

The analysis of repeatability for the cued IVS measurements is summarized in Table 2.

Table 2.   IVS Repeatability Analysis

Stability of the recovered polarizabilities

Metric: Deviation from the reference
total polarizability at 0.5 ms:
- IVS#1: 0.7 to 1.3 or within factor 1.5
- IVS#2: Empty hole
- IVS#3: 0.7 to 1.2 or within factor 1.5
- IVS#4: 0.8 to 1.3 or within factor 1.5
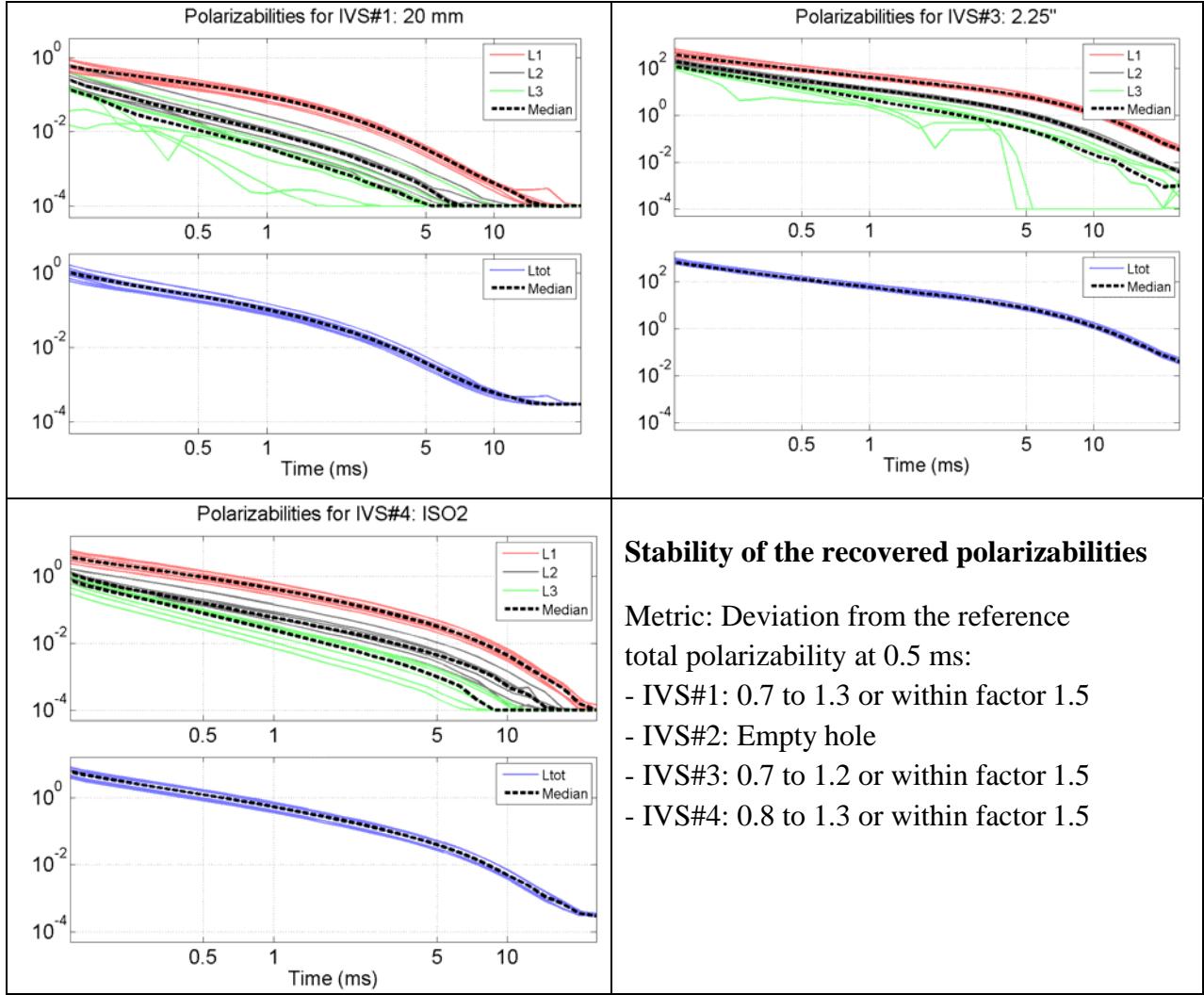
7.4 CLASSIFICATION WITH CUED DATA

7.4.1 ROC curve

The overall classification performance can be summarized with the ROC curve produced by IDA and presented in Figure 12, which shows that 95% of the TOI were found before the dig point, with three missed TOI after the dig point. The large proportion of TOI relative to non-TOI is illustrated in Figure 13.
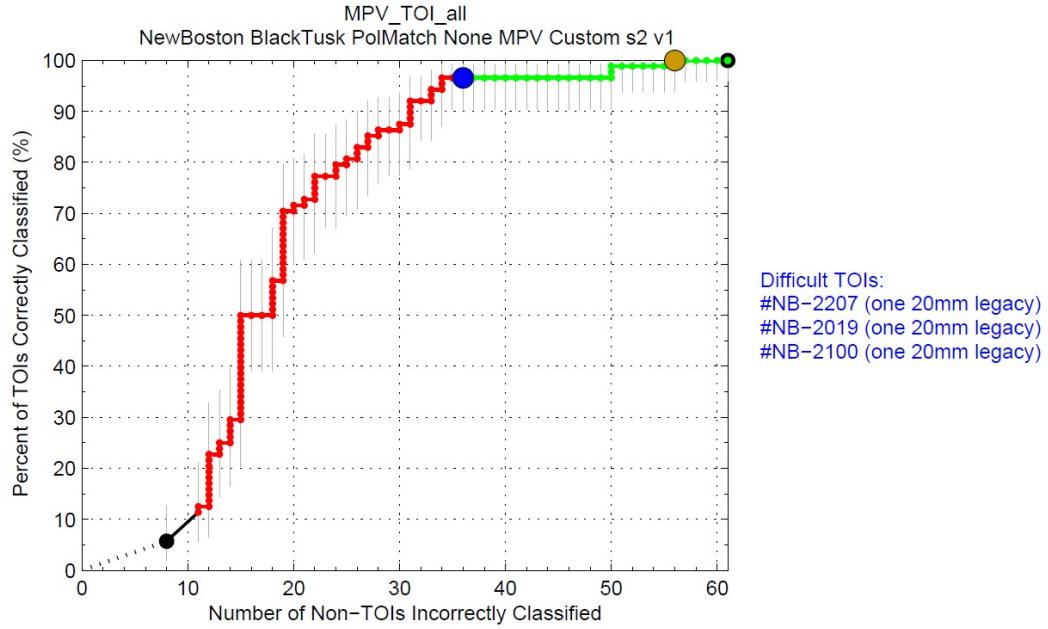
Figure 12.   ROC Curve for the MPV Cued Data Classification

	Non-TOI	Small TOI	Medium TOI	Large TOI	Total
Non-TOI	25	34			59
Small TOI	3	65	2		70
Medium TOI					
Large TOI					
Total	28	99	2		129

Small TOI (diam<50mm)
Medium TOI (50mm<=diam<100mm)
Large TOI (100mm<=diam)

Figure 13.   Distribution of TOI and Non-TOI for Dig List and Ground Truth

7.4.2   Dig list analysis

The prioritized dig list is illustrated in Figure 14 and Figure 15, where recovered polarizabilities are shown following their rank. The first 13 items were requested for training to test the presence of TOI other than 20 mm at the site. The next 7 items were anomalies that could not be reliably fit and analyzed due to data quality issues.
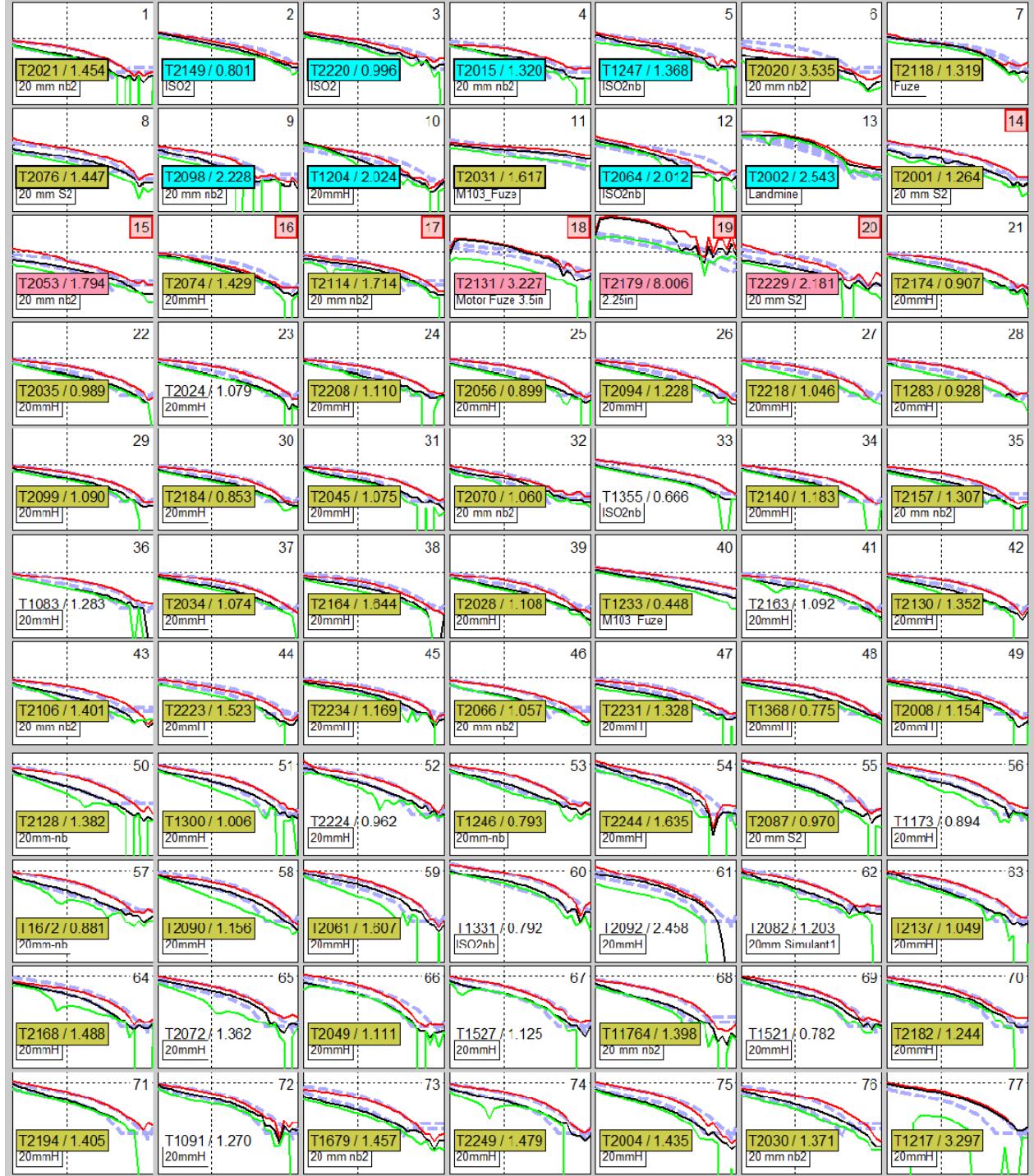
Figure 14.   Anomaly Polarizabilities in Dig List Order for Digs #1-77

*Each panel shows the predicted polarizability decay curves (in color) relative to the closest
reference item (in grey). The anomaly label (e.g., T1217) is indicated just below the decays with its
associated misfit. The text is highlighted in light green for TOI. The closest TOI type is reported
directly below. The rank is indicated in the top right corner. The first 13 items were selected for
training; the following 7 items were labeled as "cannot analyze".*
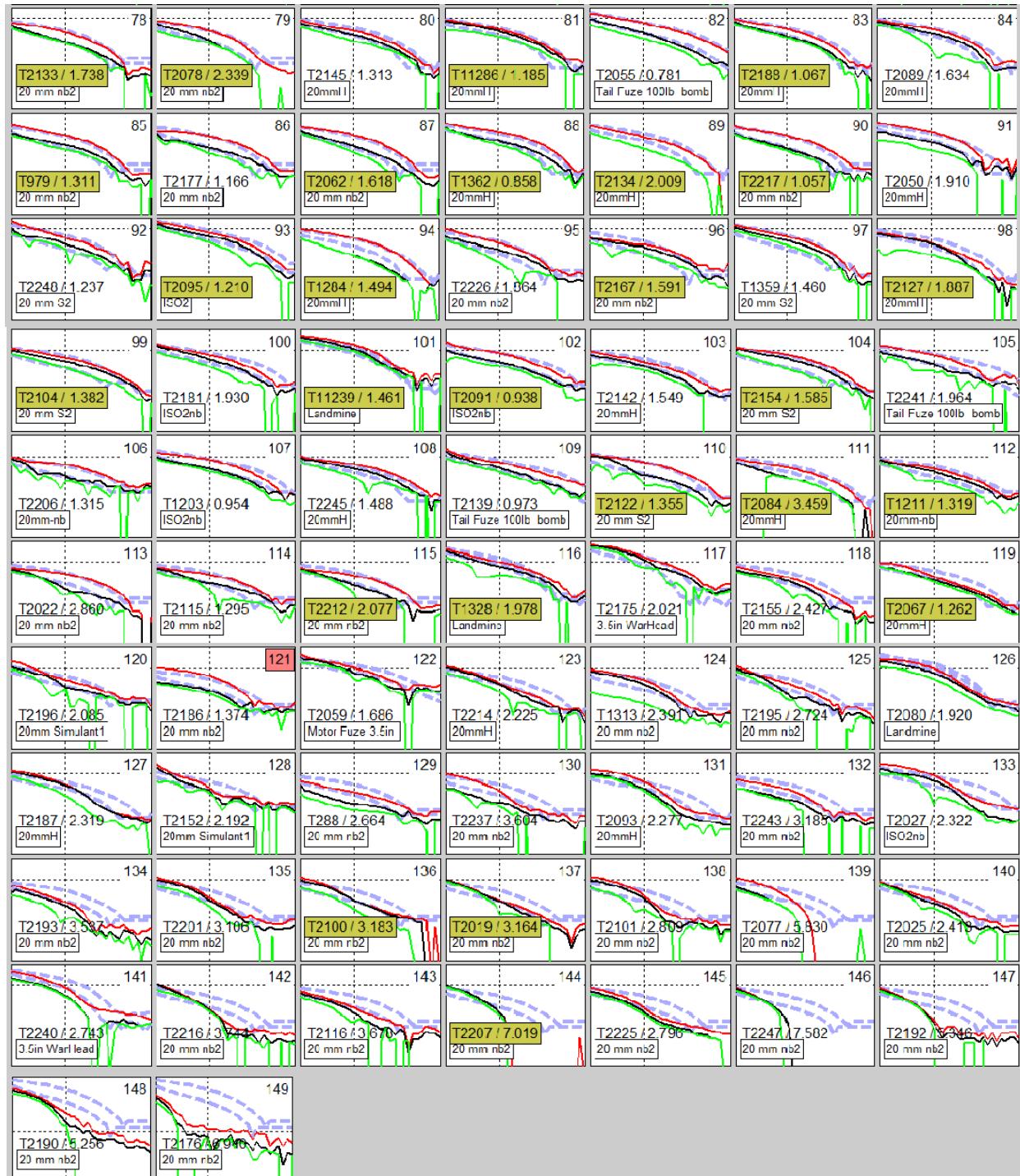
Figure 15.   Anomaly Polarizabilities in Dig List Order for Digs #78-149

The stop-dig point at rank 121 is indicated with the rank highlighted in red. Missed TOI appear at rank 136, 137 and 144 out of 149 anomalies.

7.4.3 Missed targets of interest

A summary of the anomaly characteristics is presented in Table 3. All missed TOI were located in the forest. Anomaly NB-2019 was complicated to interpret because of problems with the orientation sensors, which seems to have been turned off or be frozen during the measurements. That anomaly was classified by first solving for all the target parameters plus the sensor azimuth of each measurement and selecting the model that would fit the observed data and best fit a 20 mm projectile. The process achieved an acceptable data fit (Figure 16) but the recovered models failed to reveal a 20 mm projectile. Anomaly NB-2100 had a lesser problem; only the boom orientation was unreliable (drifting or frozen), which required solving for the target parameters plus only one angular offset to be applied to all measurements. A high quality data fit was obtained (Figure 17) and no derived models resembled a 20 mm projectile. The data for anomaly NB-2207 were deemed to be reliable and were fit (Figure 18) with high confidence that there was no 20 mm projectile.

Table 3.   Summary for Missed TOI

NB Label	Ground truth	Data quality	Closest model to ref TOI	Data fit quality for closest model
2019	20 mm + cartridge	No valid AHRS data for MPV and beacon boom	One model with similar decay as 20 mm projectile but smaller amplitude	Poor data fit for this model. There were models with better data fit
2100	20 mm	Beacon boom orientation estimated (AHRS issue)	All models resemble cartridge	Good data fit
2207	20 mm + cartridge	No issue	Models resemble cartridge or smaller item	Good data fit
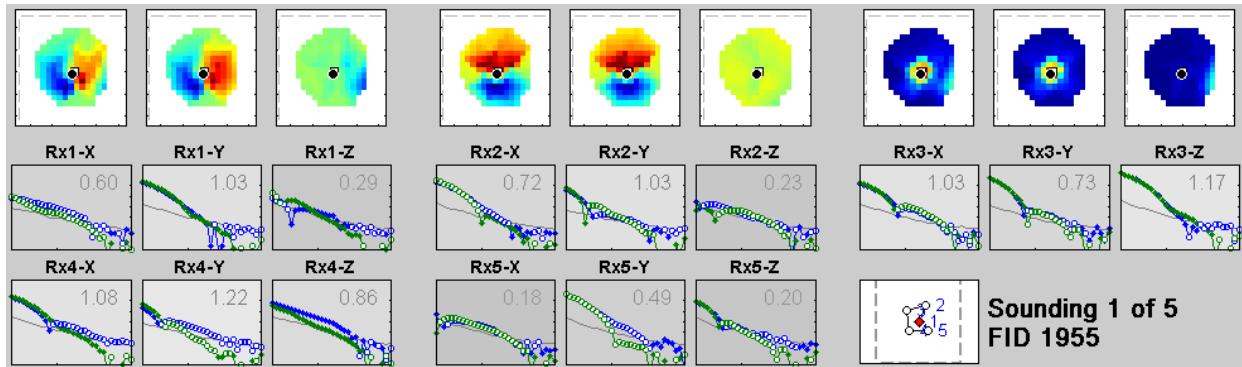
Figure 16.   Data Fit for NB-2019

The top row shows gridded images, from left to right, for the observed data, the predicted data and the residual, starting with the X-component data, then the Y-component data, and finally the Z-component data.
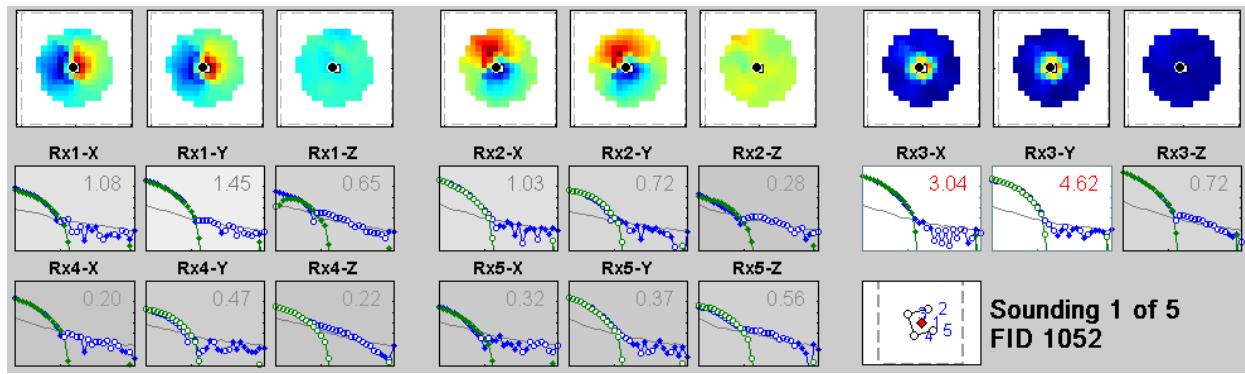
Figure 17.   Data Fit for NB-2100
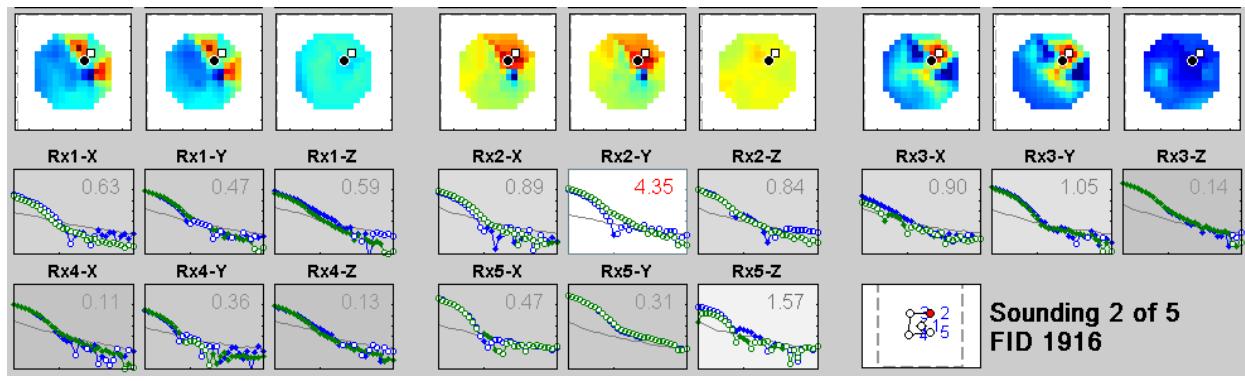
Figure 18.   Data Fit for NB-2207

7.4.4   Predicting target location and depth
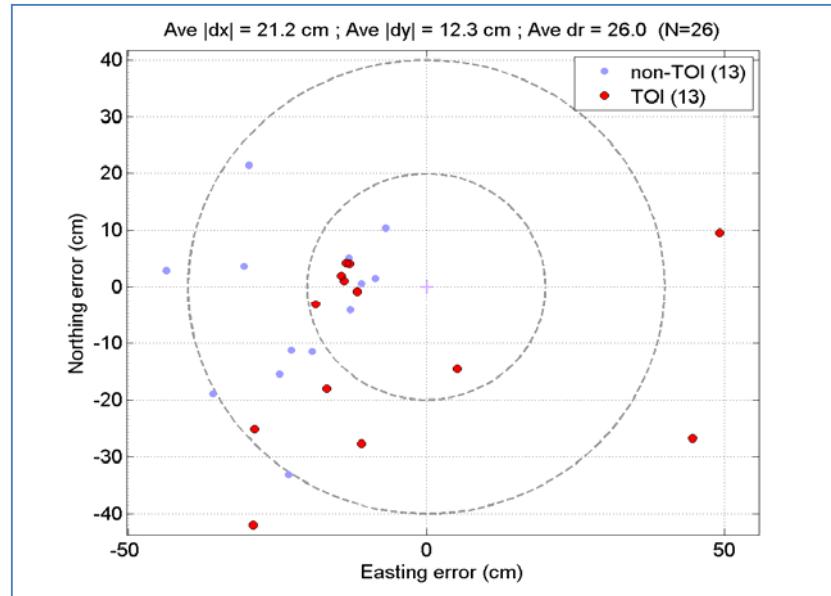
Figure 19.   Prediction of the Target Location by Inversion

The predicted target location was compared to the ground data for the open field. The difference between predicted and observed location is presented in Figure 19. There seems to be a 0.1-m bias for the Easting. Correcting for that bias, there remains several outliers beyond the 0.15-m limit offset. Examination of the predicted locations with the EMI data and with the ground truth suggests that these outliers are reporting artefacts due to the presence of multiple items associated with the anomalies.

Offsets between predicted and recovered depths are shown in Figure 20 for the entire site. Depth is predicted within 0.1-m of the dig results for 80% of the TOI. All outliers correspond to multiple- target scenarios or frag pits: the item predicted at 0.42-m depth instead of 0.04 m corresponds to a frag pit where one model predicted a large landmine, which would be deeper than the recovered 20 mm projectile; the next outlier of 0.31 m instead of 0.14 m is also a 20 mm in a frag pit where a large item was present and fitted to a landmine.
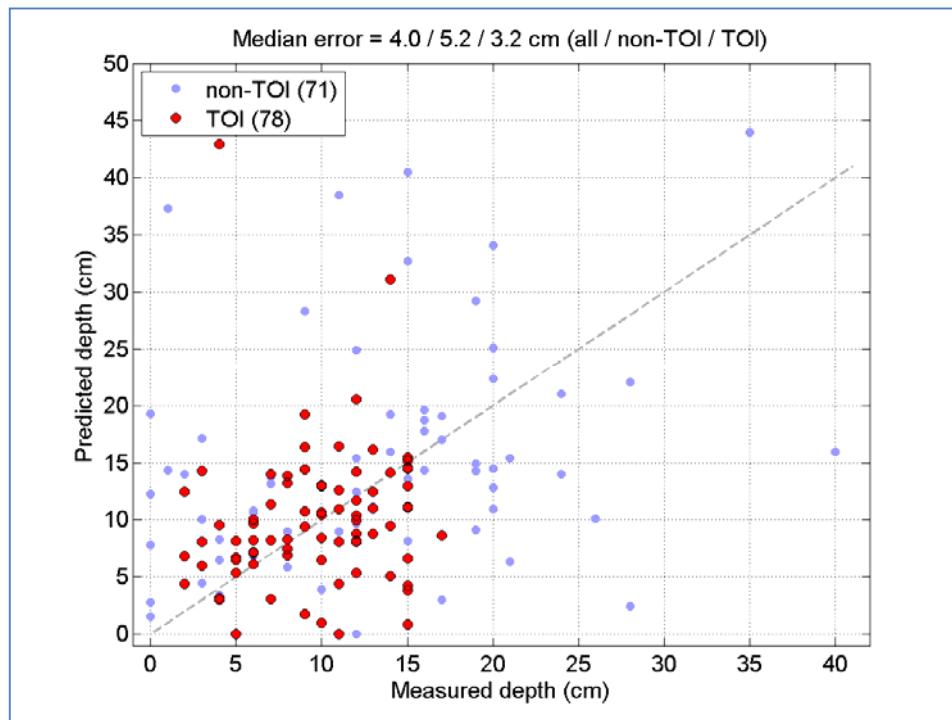
Figure 20.   Prediction of the Target Depth by Inversion

8.0 COST ASSESSMENT

Time and resources were tracked for each task to assess the cost of deploying the technology at future live sites. A cost model is proposed in Table 4, assuming an hourly rate of $100. The project geophysicist was present on site for the first ten days while the two field crews stayed for 14 days.

Table 4.   Cost Model for the MPV Demonstration

Cost Element	Data to be Tracked	Unit Time	Total Hours	Total Cost
Survey preparation and set up				**$ 38,200**
Sensor maintenance	Unit: $ Cost • MPV maintenance			$5,000
Pre-survey activities	Personnel: Geophysicist • Demonstration plan and coordination • Preparation of survey data		80 h 40 h	$8,000 $4,000
Development time	Personnel required: Geophysicist Time to test target picking algorithms Time to review AHRS integration for beacon Time to test and implement positioning method derived from azimuth (woods)		10 h 10 h 40 h	$1,000 $1,000 $4,000
Mobilization and demobilization	Cost to mobilize to site: 3 people • Flight, hotel, per diem and time • Shipping	8 h 2 h	48 h 4 h	$9,000 $3,000
Instrument setup	Typical field crew: Geophysicist + 2 technicians • First day: assemble, set up and test pit • Last day: packing	8 h 4 h	24 h 8 h	$2,400 $800
Field survey: Daily tasks (14 days)				**$16,000**
Rentals, materials and miscellaneous	Survey equipment rental (GPS) Material supplies Travel to site, car rental, hotel and per diem	 1 h	 3 h 34 h	$3,000 $1,000 $5,500
Instrument verification	Typical field crew: Geophysicist + technicians • Typical day (GPS set up and IVS surveys) • Analyze IVS data (Geophysicist)	1 h 0.5 h	14 h 7 h	$1,400 $700
Technical interruptions	Troubleshooting personnel: Geophysicist + 2 technicians + Programmer • Field tests (geo+tech) • Software modification and testing (geo+prog)		24 h 20 h	$2,400 $2,000
Field survey: Detection (1 acre)				**$8,000**
Data collection for detection	Field personnel : Field crew of 3 Crew: Time to layout survey, collect & record data per acre Geophysicist: Training	20 h 4 h	40 h 4 h	$4,400
Detection: Data extraction, QC and anomaly selection	Personnel: Geophysicist Data extraction and QC (per acre) Built detection map, establish threshold, pick anomalies and produce memo	20 h 16 h	20 h 16 h	$2,000 $1,600

Table 4. Cost Model for the MPV Demonstration (Continued)

Cost Element	Data to be Tracked	Unit Time	Total Hours	Total Cost
Field survey: Cued interrogation (500 anomalies)				**$16,000**
Data collection for cued survey	Training/Overview: Geophysicist		10 h	
	Data collection: 2 field technicians	5 min	85 h	$9,500
Pre-processing and QC	Personnel required: Geophysicist			
	Cued data: Cost per flag	3 min	25 h	$2,500
	Cued data: Additional analysis post survey		40 h	$4,000
Classification of cued interrogation data (150 anomalies)				**$4,000**
Parameter extraction	Personnel: Geophysicist			
	Time for characterizing data quality	5 h	5h	
	Time for inversion, QC and model selection	5 min	13 h	$1,800
Classifier training	Personnel: Geophysicist			
	Time to identify features and potential TOI	2.5 min	12 h	$1,200
Classification and dig list	Personnel: Geophysicist			
	Time for memo and groundtruth assimilation	2 min	20 h	$2,000
COST SUMMARY				
Dynamic data collection per acre				**$4,400**
Detection map and analysis per acre				**$3,600**
Cued data acquisition and QC per anomaly				**$32**
Cued data classification per anomaly				**$27**

9.0   MANAGEMENT AND STAFFING

A flow chart showing the managerial hierarchy and the relationship between the principal investigator (PI) and other personnel is shown in Figure 21.
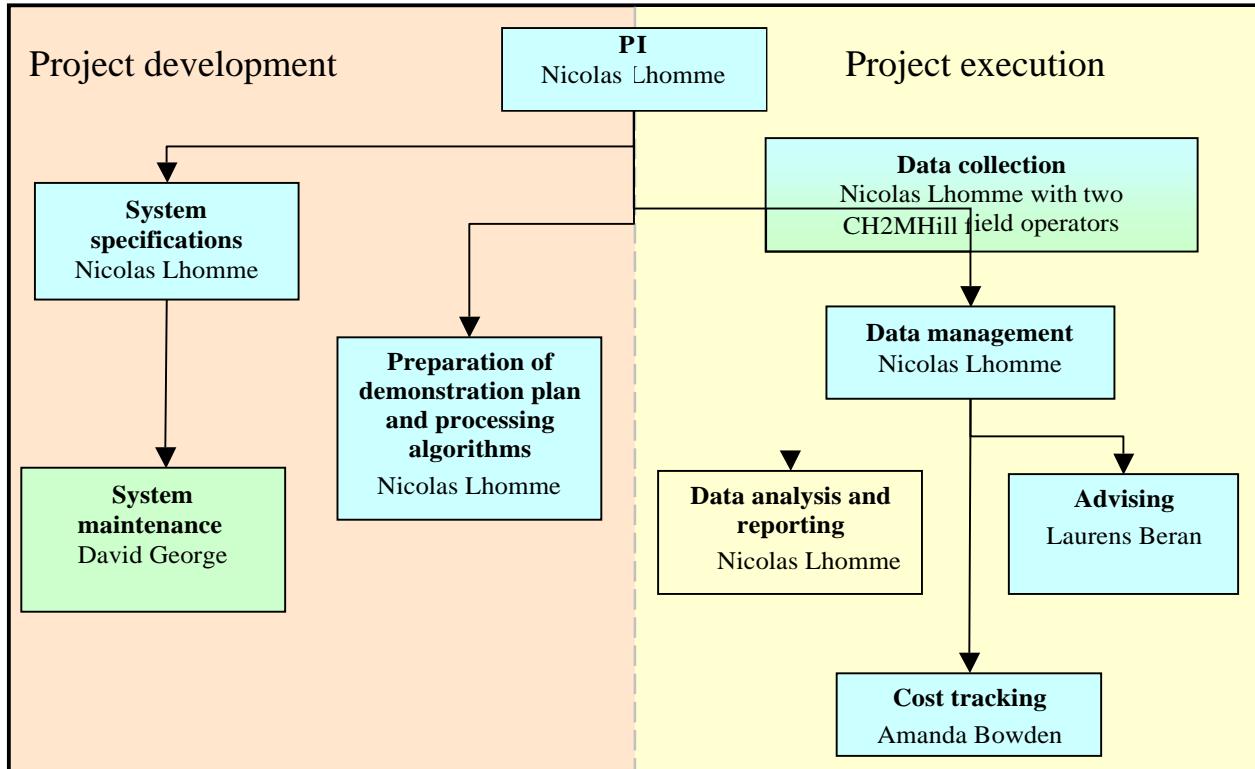

Figure 21.   Project Management Hierarchy for Spencer Range Demonstration

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10.0 REFERENCES

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APPENDIX A   POINTS OF CONTACT

Points of contact (POCs) involved in the demonstration and their contact information are presented below.

Point of Contact Name	Organization Name Address	Phone Fax Email	Role in Project
Dr. Nicolas Lhomme	Black Tusk Geophysics 401-1755, W Broadway Vancouver, BC V6J 4S5, Canada	Tel: 604-428-3382 Nicolas.Lhomme@btgeophysics.com	Project PI
Jeffrey Oja	Air Force 23 SOPS/CEA 317 Chestnut Hill Rd. New Boston AFS, NH 03070-5125	Tel: 603-471-2417 jeffrey.oja@us.af.mil	Restoration Program Manager Local Liaison
Tamir Klaff	CH2MHill 18 Tremont St Suite 700 Boston , MA 02108	Tel: 202-596-1199 Tamir.Klaff@ch2m.com	Industry Partner
David George	G&G Sciences, Inc. 873 23 Rd Grand Junction, CO 81505	Tel: (970) 263-9714 Fax: (970) 263-9714 dgeorge@ggsciences.com	Sensor manufacturer
Amy Walker	US Army Corps of Engineers Engineering and Support Center, Huntsville	Tel: 256-895-1604 Cell: 256-503-8403 Amy.N.Walker@usace.army.mil	Geophysicist QC and cued list selection
Dr. Herb Nelson	ESTCP Program Office 901 North Stuart Street, Suite 303 Arlington, VA 22203-1821	Tel: 571-372-6400 Herbert.Nelson@osd.mil	ESTCP Munitions Management Program Manager

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APPENDIX B   CH2MHILL AFTER-ACTION REPORT

CH2MHILL ®

MPV Report for New Boston AFS Demonstration

PREPARED FOR	Nicolas Lhomme (BTG) Tamir Klaff (WDC) David Wright (BOS)	**PREPARED BY:**	Jennifer Weller (FLL)
		DATE:	April 28, 2016
COPY TO::	Tom Roth (ATL) Victoria Rystrom (DEN)	**PROJECT NUMBER:**	478489

With support from the Environmental Security Technology Certification Program (ESTCP), Black Tusk Geophysics (BTG) is developing an advanced electromagnetic induction (EMI) system for UXO detection and characterization. Called the Man Portable Vector (MPV), the system draws elements of its design from other advanced systems currently being developed, but is designed to be man portable and easily deployed in environments that other advanced EMI systems cannot access.

CH2M HILL Constructors, Inc. (CH2M HILL) serves as a subcontractor to BTG. Under this contract, CH2M HILL assisted with the collection of dynamic and cued geophysical data using the MPV EMI sensor, in the ESTCP Munitions Response Live Site Demonstration at the Shooting Fields located at New Boston Air Force Station (NBAFS), New Hampshire.

The demonstration at NBAFS was one in a series of ESTCP demonstrations of various classification technologies specific to Munitions Response (MR). The demonstration was designed to investigate the MPV's detection and classification abilities at a site that includes a densely wooded area where surveying presents a challenge. The MPV sensor is designed to extend advanced discrimination capabilities to sites with difficult surveying conditions and thus allow for advanced discrimination to be applied at most human trafficable land locations at moderate cost.

The system was deployed first in dynamic search mode to test detection capabilities and then in cued interrogation mode to characterize targets selected from the dynamic survey. Approximately 1,200 targets were identified in the open field dynamic survey and approximately 700 targets were identified in the wooded dynamic survey area. Due to the unexpected high density of anomaly sources identified from the dynamic survey, the geographic area for the cued investigation was reduced so that the southern half of the grid could be characterized. Within the area selected for characterization, 259 targets in the open and 240 targets in the wooded area were retained for classification in cued mode by collecting multiple static soundings. This memo provides a brief summary of the demonstration design and CH2M HILL's field efforts.

M E M O R A N D U M
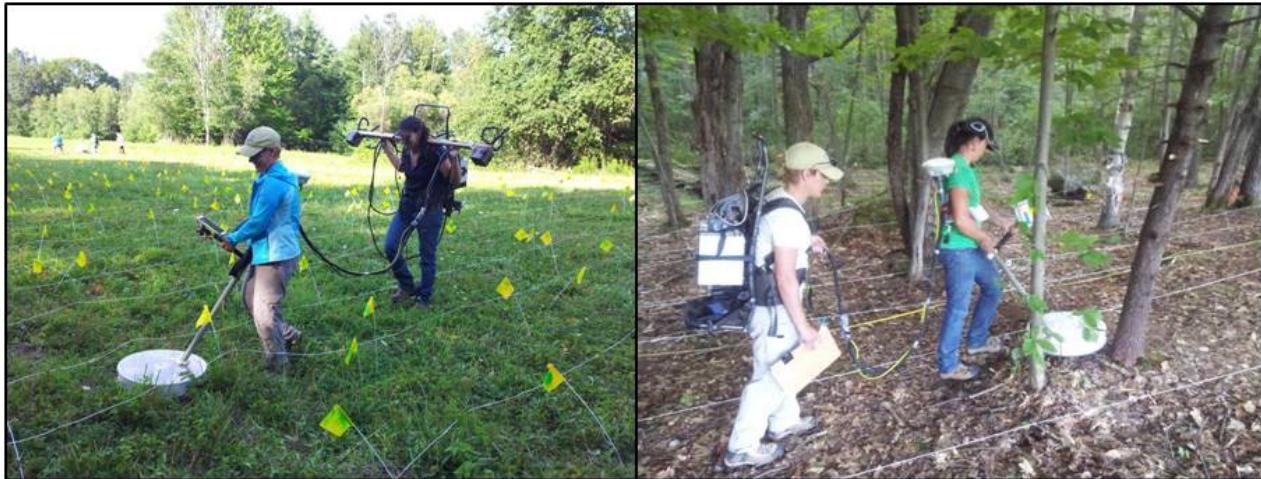
Equipment Design and Use

The MPV is a man-portable system that requires two operators for use (Figure 1). Four primary components make up the MPV—a backpack carried by one operator, a sensor unit carried by the other user, a control display, and a beacon used for positioning cued data. The backpack has an aluminum frame and shoulder straps configured to be wearable on the back of a user. The frame carries a data acquisition unit that receives and records data from the sensor unit. The data acquisition unit receives power from a battery bank within a power unit that is also attached to the backpack frame. The backpack weighs over 30 pounds. A tether of approximately 3 meters in length comprising data and power cabling connects the backpack to the sensor unit. The sensor unit is made of a PVC boom having the sensor head at the lower boom terminus and a GPS antenna proximate the upper terminus (the GPS antenna can be removed for non-GPS positioned surveys). A handle and arm cuff are disposed on the boom to provide a means for carrying the sensor unit. The control display is a computing device (e.g. an IPad or Tough Book) that provides a touch-screen graphical user interface to an operator (typically attached to the sensor handle and operated by the person wielding the sensor unit), and wirelessly communicates with the data acquisition unit. The control display allows the user to manipulate survey parameters, and monitor system performance and survey results.

Site Description

The demonstration site was located at the Shooting Field at NBAFS, New Hampshire. The primary area of interest for the dynamic and cued MPV investigation was grid J22, an approximately 60 m x 60 m (1 acre) portion of the Shooting Field as depicted in **Figure 2**.

MEMORANDUM
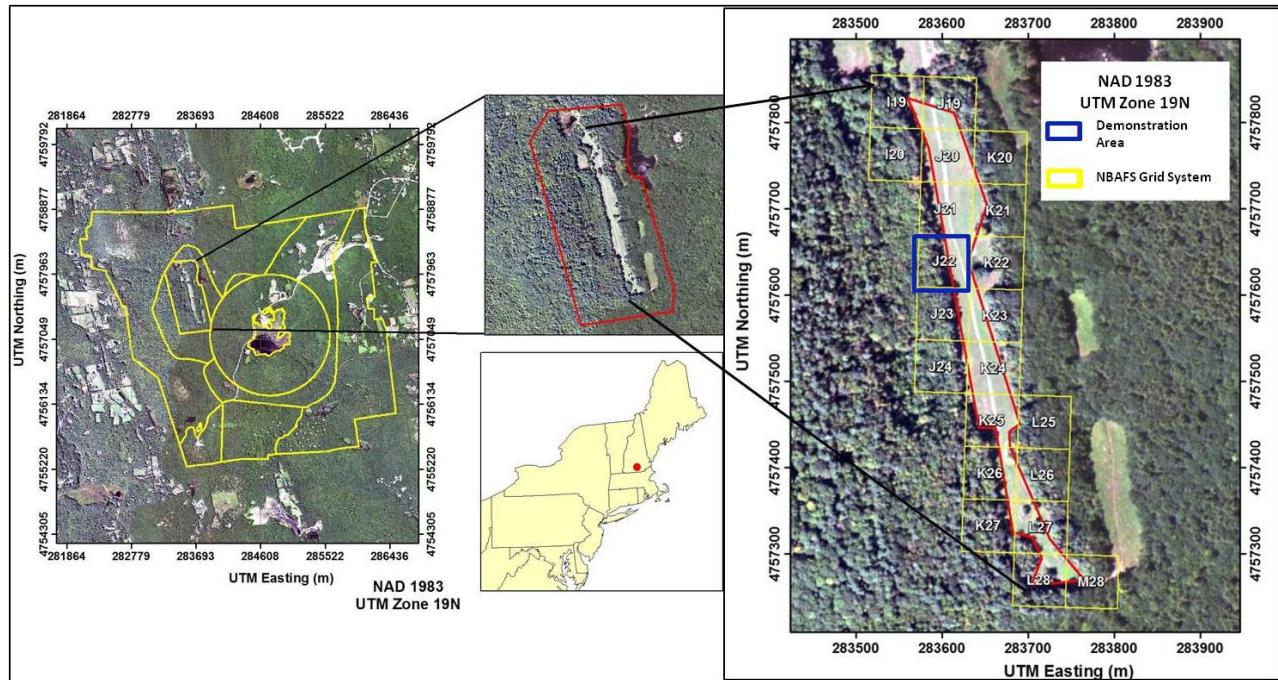
Demonstration Design

The goal of the study was to demonstrate and characterize the MPV's capability to detect and classify potential munitions items.

Demonstration Activities

CH2M HILL staff mobilized to Manchester, New Hampshire on Monday, August 5, 2013. A brief summary of the field team's activities is provided below.

Site Set-up and Troubleshooting: August 6 – August 9, 2013

The first day at NBAFS included:

- Acquiring base access passes
- Unpacking the sensor
- Assembling the sensor
- Troubleshooting issues related to sensor damage during transport
- Inspection of data collection areas (wooded and open)
- Preliminary collection of IVS data

MEMORANDUM

Upon assembly of the MPV sensor it was discovered that the power supply connector, which allows the sensor to run off batteries (as opposed to direct AC current), had broken during transport. A soldering iron was acquired and the power supply connector was fixed on site.

Concurrent with the MPV demonstration, the TEMTADS 2x2 system was also being operated as part of the ESTCP demonstration test. As both EMI instruments were collecting data in grid J22 a series of tests were conducted on August 7th at the IVS to determine the minimum operational range that both the MPV and TEMTADS 2x2 systems could successfully work without interference. The instruments were tested starting at a distance of 10 m and working outward in increments of 10 m until no interference could be seen in the data. At a distance of 30 m interference between the two systems was minimal. Allowing for a 10 m cushion, the minimum operational distance between the MPV and TEMTADS during production surveys was determined to be 40 m.

Tests with the MPV were attempted at the IVS in both cued and dynamic mode. During these tests, software issues prevented data collection. Prior to deployment for the NBAFS demonstration, modifications were made in the program logic for managing communication ports (e.g., Inertial Measurement Unit [IMU] drivers). These modifications were not compatible with the standard system configuration. Issues included:

- Freezing of the IMU drivers

- The requirement to keep the beacon connected in dynamic survey mode (the beacon is typically only used in cued mode)

- The need to plug in the beacon and GPS USB connections in a specific order after the central processing unit (CPU) had booted up.

- Corruption of the data stream

- Data gaps in the detection map

- The need to set the COM port and GPS to a lower baud rate

- Positional offset in the loaded track path

- WiFi drop-outs

The issues involving the IMUs were resolved through modification of the DAQ software and troubleshooting to record error events. All additional issues were resolved through field QC procedures, such as modification of the expected baud rate, and updating the GPS configuration and the DAQ parameter file. Nicolas Lhomme made the necessary modifications and corrections from August 7 – 8, during which time the set up (e.g. measuring and marking survey lanes and laying out guide ropes to assist with navigation) for the wooded area survey took place. On August 9 the newly configured MPV system was tested at NBAFS. Most of the issues were resolved. The need to plug the beacon and GPS USB connections in a specific order continued to be an issue. On the final day of collection there was an unexplained reassigning of the IP address of the CPU which resulted in loss of communication to the CPU by remote desktop. As a solution a monitor was connected to the MPV through the USB port.

M E M O R A N D U M

Dynamic Data Collection

Dynamic data collection over 0.9 acres in open and wooded survey areas took place over August 10–11, 2013. A small portion of the wooded area in the southwest portion of grid J22 was not collected during the survey as heavy rains resulting in large pools of standing water and deep mud made the area inaccessible to the field team.

Cued Data Collection

Cued data collection took place from August 12–19, 2013. A total of 259 targets in the open and 240 targets in the wooded area were investigated. Reacquisition of targets in the open area was achieved through real time positioning using RTK GPS. Reacquisition of targets in the wooded area was achieved by measuring the distance down-line (distances and line numbers were provided by Nicolas Lhomme) and marking the location with a non-metallic pin flag and marking paint. Each flag was labeled with the target ID, down-line distance, and line number.

The MPV was then used to refine the position of each anomaly source and the cued measurements were taken from the refined position. The position of the pin flag was adjusted to reflect the center of the first cued reading.

In some cases the MPV could not be positioned over the center of the anomaly source and/or one of the cued positions due to an obstruction (e.g. rock, root, or tree). In these cases additional soundings were taken as reasonable to image the anomaly source.

Summary

Over the course of field activities the CH2M HILL observed a number of advantages associated with the MPV sensor. These include:

- The sensor is able to be deployed in both open environments as well wooded environments characterized by challenging terrain and obstacles such as trees, rocks, and roots.

- Compared to other EMI technologies the MPV is relatively small, maneuverable, and man portable.

- The ability to "hot swap" batteries. This allows batteries with a low charge to be replaced without necessitating shutting down and rebooting the CPU.

- The transparent sensor head allows the sensor operator to accurately position the cubes over the desired location.

- The ability to quickly assess the "size" of an anomaly from the first cued reading and adjust the radius of the cued measurement footprint.

- For cued interrogation of targets identified in the wooded area, the MPV is both efficient and practical compared to other technologies available.

Several disadvantages associated with the MPV system were also noted. These include:

- The sensor design is not optimized for different users.

- – The MPV is very uncomfortable/unwieldy for smaller users to operate for long periods of time; the sensor needs improvement in design and ability to adjust to different body types and sizes.
- – There is variability in collection parameters (e.g. sensor height above ground, sensor collection pattern, and sensor coverage of survey lane) due to the inability to adjust sensor set up in a comfortable, standard manner for individual users.
- A lack of stability in the software platform which resulted in multiple-day delays to resolve issues and recollection of data.
- Dynamic surveys in wooded areas require more time than an equivalent EM61 survey.
- Replacement parts are not readily available to address issues with broken equipment. Acquisition of soldering tools and soldering skills required.
- Technical support for programming/software issues effectively limited to one person.
- The need to record each file number for each cued reading in a notebook.
- Final position of non-GPS data is dependent on the accurate measurements of the stop and start positions on the transect and the pace of the data collector. It was shown that between three different operators the style of sensor swing and pace of data collection varied.

Conclusions

Based on the CH2M HILL field team's experience using the MPV at the ESTCP Munitions Response Live Site Demonstration at the Shooting Fields located at NBAFS, it is concluded that the platform performs well when configured correctly—particularly in wooded areas when in cued mode. There are, however, several disadvantages that must be addressed, including poor ergonomic configuration that is not comfortable to a range of users, an unstable software platform, and limited technical support capabilities.